THE GREAT ENGINEERS

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'MAKERS OF SCIENCE,' 'THE GREAT PHYSICISTS,'
ETC.

WITH 33 DIAGRAMS

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THE GREAT SCIENTISTS

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PREFACE

THE author, in his desire to pay due tribute to the Great Engineers who form the subject title of this small volume, has been compelled by limitations of space to impose severe restrictions upon his treatment. To roam indiscriminately over the very wide field that is offered by the history of engineering science is a plan that could only result in detached and disconnected chapters. On the other hand, to attempt a chronological survey of engineering progress is a task quite beyond the possibilities of even a single volume many times the size of this one. Continuity is nevertheless, in the author's view, the preferable alternative, and he has therefore endeavoured to achieve this by offering first a preliminary survey of the engineering of Classical Antiquity and of the beginnings of engineering science as a formal study in the Middle Ages; and then to proceed to the story of those Great Engineers of the more recent past who gave to civilization Man's control over Power and Materials. Iron and Steel are the raw materials of Engineering; the Steam and the Internal-Combustion Engine supply the Power. Upon these two factors the whole of the superstructure of engineering achievement has been built. The author therefore hopes that it is pertinent, in this small work, to confine his story within these limits—at least the result is a connected narrative.

As with the earlier volume in this series, no claim is made to originality other than that of treatment. The author has drawn freely from many sources, and special acknowledgements are due to the *Transactions of the*

Newcomen Society; to Thurston's *History of the Steam Engine*; Galloway's *Steam Engine and its Pioneers*; G. Dugald Clerk's *Petrol, Gas and Oil Engines*; Turner's *Metallurgy of Iron*; Hoover's fine translation of Agricola's *De Re Metallica*; Salzman's *Medieval English Industries*; and to Ashton's *Iron and Steel in the Industrial Revolution.* Grateful acknowledgements are due to Mr. C. L. M. Brown, M.A., for the careful and critical reading of the manuscript; to Dr. Charles Singer for the reading of the proofs; and to Mr. W. Laidler, B.Sc., for valuable assistance with the diagrams.

IVOR B. HART

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THE GREAT ENGINEERS

CHAPTER I

ENGINEERING IN CLASSICAL ANTIQUITY

I. PHILOSOPHY AND ENGINEERING

IN this record of the lives and work of some of our great engineers we are bound of necessity to find that two forms of scientific activity present themselves. There is the abstract science—the fruits of ordered speculation—which, leading to the discovery of a principle or law of nature, is turned to practical account and applied to invention; and there is, conversely, the practical invention based on the evolution of continual experience, which gives rise to a study and an understanding of the laws upon which it is based. It is natural that in the early history of mankind, this latter type of scientific progress should have prevailed. Not that speculation was absent. On the contrary, Greek philosophy was largely a matter of speculation over a very wide field, but it was, on the whole, mainly a cosmological field. Here again, however, it must not be supposed that the philosophers of antiquity were as a whole mere speculators in the realms of science. Their interests were frequently very wide. A happy example is afforded by Thales of Miletus (*c.* 600 B.C.), so commonly regarded as the earliest of the Greek philosophers. Thales was an astronomer and a geometer. He propounded the theory that water was the prime material whence all

matter came. Yet he was also a politician and a trader, and a man with a practical outlook. The apocryphal story of his cornering of the world market of vines is at least of value in illustrating one side of his activities. Further, and this is the particular point we desire to stress here, if Thales was not an engineer, he was at least capable of inspiring engineering achievement. Thus we read of him that when Croesus was advancing against the Persians and his army was held up by the River Halys, it was Thales who suggested the diverting of the waters of the river by the construction of a canal, so that the army could get across. A similar and even more effective illustration is afforded by Harpales (*c.* 480 B.C.), a well-known astronomer who succeeded Cleostratus in the direction of the School of Tenedos, originally founded by Thales. This astronomer has been identified, by the aid of a papyrus recently discovered at Fayoum, known as the '*Laterculi Alexandrini*', with the hitherto unknown performer of the wonderful feat of military engineering whereby Xerxes and his army made their famous crossing of the Hellespont after the failure of a previous bridge of boats.

The difficulty in those early days was not that a philosopher could be an engineer, but that he could not, or did not, bring his philosophy and his engineering into adequate relationship to each other. When, ultimately, there came a better understanding of the principles of exact measurement, the writings of the engineers, such, for example, as those of Ctesibius, Archimedes, Heron and Vitruvius, reflected a new spirit, so that science became more mechanical, and mechanics more scientific.

II. EARLY ENGINEERING FEATS—AQUEDUCTS

Some of the earliest problems of large-scale engineering were concerned with the conveying of water for drinking and other purposes to a city from a distant source. In Egypt and Mesopotamia, owing to the flat nature of the country, and the liability of its rivers to flooding,

irrigation was largely carried out by the aid of canal systems, a striking example being the system of five canals radiating from the waters of the Diahlah north of Baghdad, built by Nebuchadnezzar, King of Babylon early in the sixth century B.C. The remains of these even to-day are a striking testimony to the efficiency with which they were constructed. Where the contour was not so simple, however, other devices had to be employed. The geological formation lent itself in some cases to the digging of artesian wells, in connection with which water-towers were successfully used. An example of this is seen in the Phoenician erection of the wells of Ras-el-Ain, near Tyre. Four wells were sunk, and over each was a strong octagonal tower, whence the accumulated waters were led by conduits to reservoirs near the shore. Later the Romans conveyed the water across to the island (previously carried in vessels or skins) by means of an aqueduct.

Aqueducts were either tunnelled through hills or carried over bridgework, according to the nature of the ground. The tunnelling operations naturally called for skill and accuracy in maintaining direction, and the instruments employed for this purpose in Roman and Greek times will be considered later. Before their use, however, the methods, and therefore the results, were not too happy. An interesting example of this is the tunnel which was constructed about 700 B.C. by Hezekiah, one of the Kings of Judah, for supplying the city of Jerusalem with water in the event of a siege. The two boring parties, working from either end, were so uncertain of their direction that at intervals they pierced air-shafts above them as a check on their alignment, in spite of which they nearly passed one another. The zigzag result will be evident from the fact that what should have been a straight line of some 1,100 feet, became an aqueduct of over 1,700 feet. It is interesting to note the evidence upon which it is believed that borings were carried out from both ends. The tool-marks are seen to run in opposite directions from the

ends to the middle. Even with the help of instruments, however, the alignment was not always successful. Thus the Roman engineer, Nonius Datus, sent in the following very human report regarding the blunder made during the excavation of a tunnel at Saldae, in Algeria, in the year A.D. 152:

'I found everybody sad and despondent. They had given up all hopes that the opposite sections of the tunnel would meet, because each section had already been excavated beyond the middle of the mountain. As always happens in these cases, the fault was attributed to me, the engineer, as though I had not taken all precautions to ensure the success of the work. What could I have done better? For I began by surveying and taking the levels of the mountain, I drew plans and sections of the whole work, which plans I handed over to Petronius Celer, the Governor of Mauretania; and to take extra precaution, I summoned the contractor and his workmen and began the excavation in their presence with the help of two gangs of experienced veterans, namely, a detachment of marine infantry and a detachment of Alpine troops. What more could I have done? After four years' absence, expecting every day to hear the good tidings of the water at Saldae, I arrive; the contractor and his assistants had made blunder upon blunder. In each section of the tunnel they had diverged from the straight line, each towards the right, and had I waited a little longer before coming, Saldae would have possessed two tunnels instead of one!'

In the early days of the Greek era, when the communities were small, the water supply was usually adequately secured from natural springs and cisterns hewn in the rock. As the communities grew, however, such sources of supply became inadequate, and the age of the tyrants saw a great advance in the methods employed. One of the most successful of the engineers of those days was *Eupalinus* of Megara, who was in the service of the tyrant Polycrates. Polycrates was a lover of learning who attracted to his court and to the library which he had accumulated a large school of philosophers, and it was in this atmosphere that Eupalinus laboured. His most famous achievement was the construction of a tunnel through Mount Castro for the passage of a conduit from the water source to the town of Samos. The tunnel was 4,200 feet long, and was 8 feet high and

8 feet broad, and along it the conduit was dug to a depth of 3 feet, the water being always in contact with fresh air. It was given a natural declivity, and was led by suitable masonry to the town, where it supplied fountains, baths, pipes, and latrines, and was carried out ultimately into the harbour. The tunnel with its conduit was discovered by Greek archæologists in the year 1882 in an excellent state of preservation, and was seen to be perfectly straight. It led to a fountain under the present village of Tigani. Periodically along the tunnel were found the niches in which the workmen placed their lamps and tools during the processes of construction.

III. ROMAN ATTITUDE TOWARDS SCIENCE

When we turn to the Roman works of large-scale engineering, we find a high state of efficiency in both theory and practice which manifested itself in the making of roads, in the building of bridges, and in the erection of fortifications. The Romans, unlike the Greeks, were not abstract philosophers. Their science was mainly utilitarian and practical. They were inspired in its pursuit only so far as it served to reflect itself in results, whether it were for their better comfort in peace, or for their better efficiency in war. Their philosophers were few. They included Lucretius (*c.* 95–55 B.C.), Varro (116–28 B.C.), Pliny and Seneca (3 B.C.–A.D. 65). All these writers, in greater or less degree, were influenced by the Greek legacy of learning, and indeed their value, such as it was, could almost be measured by such influence.

In contrast with these we have the famous *De Architectura libri X* of Vitruvius, the most complete summary of the position of applied science, engineering, architecture, and technology in the Roman era. It was the standard text-book of the engineer and the architect for many centuries, but was completely lost sight of from about the tenth century A.D. On its rediscovery,

however, in the fifteenth century, in the library of the Italian church of St. Gall by Poggio, it at once found fresh favour; all the great *cinquecentist* architects and engineers of the later Italian Renaissance used it, and its fame spread far and wide.

It does not need, however, the mere testimony of such a work as that of Vitruvius to show us the high standard of engineering of Roman times. Their great structures remain with us to-day, some in decay, some in a fine state of preservation, but all of them eloquent, if silent, tributes to the great era of construction in which they found their genesis. It is an interesting fact that although engineering practice and scientific knowledge are indissolubly linked together, much can be accomplished with the mere aid of past experience together with that indefinable 'horse sense' without which the engineer is helpless. These, in fact, constituted the chief equipment of the engineers and technologists of the Roman era.

It was on this account, for example, and in spite of this weakness in the world of theory, that the organization of large-scale hygiene and sanitation in Rome was both very efficient and highly developed. The position and orientation of buildings received careful attention, and considerations of sanitation were at all times prominent. Burials were forbidden within the city walls, the water supply was assured, whilst the drainage of buildings, the provision of latrines, some of them flushed with water from a constant fountain, and the evacuation of sewerage were all carried out with efficiency. The main drain of Rome in the Tarquin era (sixth century B.C.), for example, was a noteworthy achievement. Known as the *Cloaca Maxima*, it was constructed to drain and carry to the Tiber the waters of the valley where the Forum Romanum was built. Later, in the time of Augustus, it was modified and largely reconstructed on a higher level, serving as the main sewage-channel of the city.

IV. ROMAN ENGINEERING

Turning in greater detail to the general features of Roman engineering and architecture, it may be noted, with regard to the erection of buildings, that the two chief characteristics were solidity of construction and magnificence of conception. Although stone masonry was not new to the world, Roman stone-work was far superior to any that had preceded it, and indeed to much that followed it. Thus the Venerable Bede, the Anglo-Saxon encyclopædist, proudly refers to the stone churches which were then beginning to appear as having been fashioned 'after the manner of the Romans'. In addition to stone, the chief materials employed in building were brick and concrete. Relatively light and plastic, these made the vaulting of great spans a simple matter. The durability of the concrete employed is amply evidenced by the way in which structures of that material have stood the test of time, long after the weathering and disappearance of the outer decorative coverings of brick or marble which originally concealed them. In these days the use of concrete is once again to the fore; it is reinforced with steel perhaps, but it is a return to ancient ideas nevertheless.

With regard to the other great characteristic of Roman architecture it has well been remarked that 'Egyptian architecture could be sublime; the greatest Greek temples were both sublime and beautiful, but the . . . Roman imperial buildings were magnificent.' Indeed, we can well understand that the semi-civilized barbarian hordes of Goths and Huns, mostly accustomed to live in huts or wooden houses, were stirred with feelings of awe and wonder when, in the days of its decline, they advanced towards the heart of the Roman Empire, and were 'confronted by cities built of stone, bricks and marble, boasting decorous public offices, temples, statues, mosaics and paintings, linked to one another by paved roads, mostly watered by still efficient aqueducts.' Here was

something greater than the might of the sword. Here was indeed the might of civilization.

One of the most important features in constructional conception for which we are indebted to the Romans is the development of the arch. It created a virtual revolution in the methods of bridge-building. Prior to the Roman arched bridge, there was nothing better in the shape of development from the crude bridge-of-boats scheme of Xerxes, to which we have earlier referred, than the running of platforms across sets of stone piers. At Babylon the platform over the piers across the Euphrates was of wood. At Assos, in Asia Minor, a similar Greek bridge had a stone platform. But the arched bridge comes from Rome by whom it has been handed down as a perpetual legacy to mankind ever since.

Let us turn next to the typical features of Roman road construction, the schemes of which were developed chiefly for military purposes. The roads were somewhat narrow (about 10 feet wide) and were made in long straight lines. Usually, on either side of the main road were two other roads for pedestrian use, laid down without artificial foundation. The question of upkeep, a sore point in these days, was considered then in a manner that might well be resorted to once again, namely, by rendering upkeep unnecessary as a result of the strength, firmness, and thickness of the initial construction. Usually paved, they had at least four layers, the *statumen* and the *rudus* composed of small stones with a little cement, the *nucleus* of real concrete, and the upper paving (the *summum dorsum*) formed of big blocks of basalt, shaped polygonally, and some 20 inches high. The Appian Way is one of the most famous examples of this type. It was begun in 312 B.C. by the Censor Appius Claudius Caecus, and extended originally from the Capena Gate at Rome to Capua, a distance of about 132 miles. Later it was extended, and has very truly been called the Queen of Highways. The *Via Flaminia*, begun in 220 B.C., was another long and important road.

Finally, we turn to what were perhaps, from the engineering point of view, the most wonderful works of Roman times, the fine system of aqueducts erected for the purpose of carrying water to the cities in large quantities for drinking, ornamental and irrigation purposes. Some reference to this has already been made. Frontius, one of the great engineers of those days, who occupied the post of curator of the waters in Rome under Nerva, refers to them as being magnificent beyond all comparison. The waters from the springs and rivers of the surrounding country were collected and conveyed along them, sometimes underground along tunnels, and sometimes across great arched walls, according to the contour of the ground, until they reached the reservoirs from which the distribution to the city began. Generally speaking, the down-flow of water was regulated by an open channel rather than by pressure, so that the question of gradient was of importance. Provided that the *general* gradient was down, it could occasionally be *up*. On the whole, aqueducts built across valleys were preferred to pipes carried underground. Economy was frequently the deciding factor. Underground pipes would either have to be of lead, which was weak, or of expensive bronze, or alternatively of wood or terra-cotta. The casting of large pipes for withstanding great pressure was beyond Roman skill at that time. The water, too, was hard, and the inside walls of the channels were liable to damage. They therefore required constant overhauling and repair.

In all there were no less than fourteen magnificent examples of aqueducts in Rome, and many others elsewhere.

In distributing from the reservoirs to the houses and buildings, the pressure system was employed, and judging by the specimens of plumbing which have come down to us, many efficient devices were in operation. One such was a bronze double-acting pump. It was found in Bolsena, in Etruria, and is now housed in the British Museum. The principle employed was the

invention of Ctesibius of Alexandria (*c.* 250 B.C.), and is not dissimilar in its action from the double-acting pumps of to-day.

V. EARLY INSTRUMENTS OF SURVEYING AND ENGINEERING

The instruments of surveying and engineering used by the Greeks and Romans in the setting out of roads, canals, tunnels, aqueducts, etc., were three—the *groma*, the *dioptra*, and the *chorobates*. The *groma* or *ferramentum* was used for setting out right angles. An actual specimen was recently found, together with other mathematical instruments, at Pompeii, whilst still more recently an Egyptian specimen has been brought to light by Sloley, and is of Græco-Egyptian times. The groma consisted of two horizontal cross-pieces pivoted about a vertical axis (Fig. 1). From the extremities of each end of the cross-pieces were suspended a plumb line and bob. Frontinus describes the use of the instrument as follows:

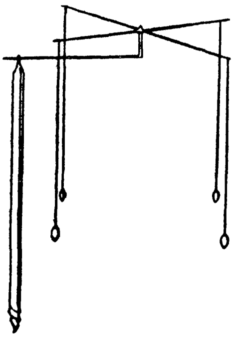


FIG. 1.—The Groma.

'To use the instrument we must steady all the plumb lines and look at the cords or string stretched by the weights, setting them in a line until the eye can see the nearest only. Then put in the stakes, and having carried the apparatus to the last stake, set up as before and look at the stakes in the opposite direction by way of a check. Then, to continue the staked-out line when interrupted by obstacles, carefully set out the right angles given by the plumb lines by perpendicular lines at every point of interception.'

Heron of Alexandria objected to this instrument because of the difficulty of preventing the plumb lines from

swinging. Nevertheless, as both agriculture and town planning were mainly carried out on rectangular lines, there is no doubt that the groma was widely used.

We turn next to the *dioptra*, an instrument with which is usually associated the name of Heron of Alexandria, who wrote a book on its uses and applications. His claims for the instrument do not err on the side of modesty.

'It is advantageously employed', wrote he, 'for the setting out of water channels, ramparts, harbours, and buildings of every kind. It is used for many astronomical purposes in connection with the observation of the sky, such as the measurement of the distances which separate stars, their size, and the determination of the distances and the eclipses of the sun and moon. Again, it is used for geographical or surveying purposes, and for the determination of the relative positions of islands and seas and generally for the estimation of distances between inaccessible points.'

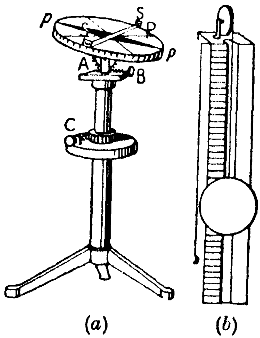


FIG. 2.—(*a*) The Dioptra, (*b*) the Levelling Staff.

The instrument as used for the setting out of lines at right angles to each other is illustrated in Fig. 2*a*. The upper plate P is graduated in degrees, and swivelling round it is a bar carrying cross-wire sights S S, at right angles to which are two pointers *p p*. Adjustment of the horizontal is assured by the control of the toothed vertical half-wheel A operated by B on the rack-and-pinion principle, whilst a similar horizontal device C gives control of orientation in a horizontal plane. Used in conjunction with this was a levelling staff (Fig. 2*b*). This was practically a long graduated rod carrying a plumb line to indicate when it was in a vertical position. A pulley wheel was mounted at the top, and from it there could be raised or lowered a disk marked with a

horizontal index. This was moved up or down until the man operating at the sights signalled that he had obtained alignment with his cross-wires; the readings and bearings were then taken, and the subsequent procedure was similar to that employed with the groma. For the purposes of water-levelling the plate P was replaced by a simple water-level of two vertical glass tubes joined by a horizontal tube.

We may claim for the dioptra, invented as it was nearly two thousand years ago, that in theory it has persisted ever since as one of the chief instruments of field measurement. Virtually it is the theodolite of to-day. The modern theodolite was the invention of Thomas Digges, who described it in his *Pantometria* in 1571 (he was the first to apply to it the term *theodolitus*),

FIG. 3.—The Chorobates.

and the only new essential features it possessed over that of its forerunner, the dioptra, were (1) the attachment of a magnetic compass for control in orientation, and (2) a definite mechanism (of which the wheel A and control B in Fig. 2*a* constituted its possible predecessor) for elevation control and measurement.

We turn finally to the third instrument of field engineering of antiquity, the *chorobates*, which Vitruvius, in his *De Architectura*, lib. 7, tells us he prefers to either the groma or dioptra. It was a large instrument, some 30 feet (20 cubits) long, whose chief features (Fig. 3) were a long rod supported on two legs, with diagonal pieces joining each leg to the rod. On each of these diagonal pieces was scratched a vertical line such that the cross-piece B C would be horizontal when each of two plumb lines at the ends were in direct

alignment with the scratch. In the event of wind disturbances making the use of the plumb lines difficult a central water channel A was employed, the horizontal being here indicated by filling it with water and observing whether the levels were the same at the channel ends.

VI. MECHANICAL DEVICES IN ANTIQUITY

We may now consider the general extent of the knowledge of mechanisms in the days of antiquity as exemplified by the mechanical contrivances employed. Of these there were a large variety, some distinctly utilitarian and essential to the easing of labour conditions and others of a more purely ornamental character designed chiefly for the amusement of the maker. Initially, of course, the strictly utilitarian aspect prevailed, and presumably the first germs of the evolution of devices for the production of what in mechanics is spoken of as a mechanical advantage resulted from the need, in the erection of buildings and monuments of various kinds, for the quick transport of materials either from one place to another, or from the ground to a place of higher elevation. In the earliest days of slave labour, the first solution was merely in the employment of slaves in sufficiently large numbers. Before very long, however, the use of wheeled transport was pressed into service, and an empirical knowledge of the lever principle was acquired.

Some of the earliest evidences of the applications of mechanical principles to the service of civilization are seen in the methods employed for the hauling of water, both from wells and from such larger works as have already been described. They are all naturally related to what in modern applied mechanics is referred to as the transmission of power. Of these one of the earliest frequently employed in antiquity was the ‘ endless chain of pots ’. These are generally regarded as having originated in the East, where, indeed, many of them have survived to this day in China, Egypt, and Mesopotamia.

The 'chain of pots' (Fig. 4) was the forerunner of the modern bucket elevator, and consisted in effect of an endless rope B carrying at regular intervals a series of earthenware pots. The rope passed over a wheel A and the lower end was submerged below the level of the water in the well C. The pots discharged their contents

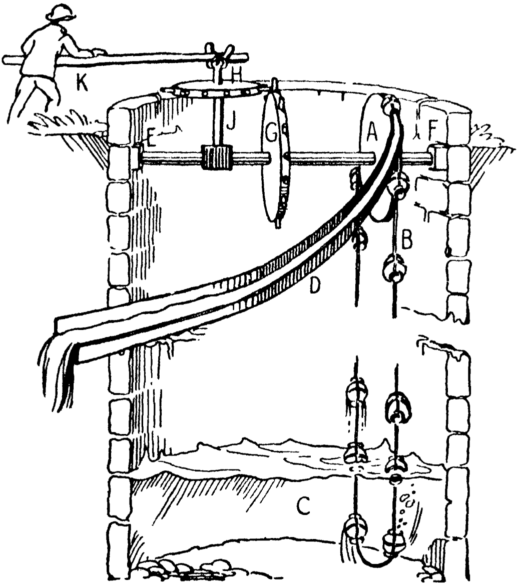


FIG. 4.—The Chain of Pots for Raising Water.

in turn into a trough D. Each pot was pierced at the base by a small hole to allow the air to escape, thus making possible the filling of the pot in an inverted position in the well. The method employed for the transmission of the power from the man or beast working the mechanism to the wheel A is interesting. The axle E F of this wheel was fixed to the two sides of the well-

wall and carried a second wheel G from which projected a number of crude teeth or spokes. These geared with a similar wheel H mounted horizontally on a vertical axis J to the top of which was firmly attached a long wooden arm K. The man or beast worked the mechanism from the end of this arm. It is believed that the water used for the famous Hanging Gardens of Semiramis was brought up to a height of 300 feet by this means, a remarkable achievement having regard to the fact that modern elevators rarely work to a height greater than 150 feet.

The use of toothed gearing is an important feature in the mechanisms of antiquity. The theory of such power transmission carries us right back to Aristotle, who in his *Mechanica* describes the possibilities of three wheels in rough contact, the first of which is made to rotate.

The development of this form of power transmission was very rapid. Thus Philo of Byzantium (*c.* 230 B.C.) not only describes an endless chain of pots, but also mentions a pump, the principle of whose working is based on the idea of the rack and pinion.

Still later, in the time of Vitruvius, the improvement in the workmanship of toothed wheels is more marked. The chain of pots, for example, has now developed into a workmanlike elevator, whilst, following on a similar mechanism devised earlier by Heron, we find in the *De Architectura* an ingenious hodometer, or instrument for the estimation of distances covered by any given vehicle. This was in a sense the forerunner of the modern taxicab.

Finally, with regard to the more general aspect of weight-lifting mechanisms in Roman times, it is clear that the use of pulleys was understood. On one of the monuments we find the mechanism of a giant crane worked by a treadmill. Although it is a little difficult to follow the details, its existence as a typical weight-lifting device is ample evidence of the advanced state of efficiency of this class of activity in the days of Vitruvius.

CHAPTER II

MEDIEVAL TECHNOLOGY

I. INTRODUCTION

IN view of the fact that much of the technology of the Middle Ages, to which we now pass, is concerned with the mining and handling of the various metals, it will be advisable to consider, by way of introduction, the general atmosphere of medieval science and of its influence upon the people of those days. With the emergence of Western civilization from the intellectual gloom of the Dark Ages there began to develop a literature, an art, and a science which were, in their way, fairly well defined. The teachers of those days contributed a number of all-embracing encyclopædias of knowledge which, in view of the non-existence of printing, attained an astonishingly wide publicity. For example, in the middle of the thirteenth century Bartholomew Anglicus wrote an encyclopædia, *On the Properties of Things*, to explain the allusions to natural objects met with in the Scriptures. It was intended for a public with practically no learning and represented fairly clearly a summary of the knowledge of the time. Yet it achieved an instant success, and was translated into many languages. Later, when the art of printing was in its earlier stages, over 200 years after the work was written, it survived edition after edition. Its ultimate demise came with the change from the typical medieval mind brought about by the transition to the modern commercial system towards the end of the sixteenth

century. So, for example, 'the man who bought cinnamon at Stourbrdige Fair in 1380 would have felt poorer if anyone had told him that it was not shot from the phoenix' nest with leaden arrows, while the merchant of 1580 wished to know where it was grown, and how much he would pay a pound for it if he bought it at first hand'.

The scientific history of those days is virtually that of the recovery of the lost learning of the old Greek philosophers—a recovery which was achieved through the agency of a growing study of the literary and scientific writings of the Arabic-speaking peoples who had already won Greek science for themselves. It is a story which has been frequently told, and with which we are not directly concerned in this work. What we are concerned with here, however, is the state of affairs in the world of medieval technology, in order that we may be in a better position to observe, with proper perspective, the evolution of engineering processes and achievements from the Middle Ages to modern times. The facts differ very little as between one country and another, and for the sake of illustration we will picture the conditions as they existed in our own country.

II. THE PRODUCTION AND PURIFICATION OF IRON

Under the ægis of the Romans, ironworks began to be opened up in various parts of the country, at Maresfield in Sussex, on the banks of the Wye, in the Forest of Dean, and elsewhere. There was a lull in the iron-producing activity during the period of Saxon rule, but the Norman period brought with it a great revival, especially during the twelfth century. For example, we read that in 1161 the monks of Kirkstead were given a site for four forges, two for smelting and two for working iron, with rights as to the digging for ore and the taking of dead wood for fuel. The Forest of Dean was undoubtedly an important area, and from its works

there issued a steady stream of iron implements of all kinds, both of peace and of war; whilst nearer London the Wealden area of Sussex and Kent became a formidable competitor.

Let us first consider the methods employed in the actual mining of the ore, and then pass on to the methods of smelting. In its most primitive form, what was known as the 'open-cast' system was employed. This could only be possible at actual outcrops of iron deposits, or where the deposits were very near the surface, and was in effect the digging of a large open cast or pit. Later, however, the 'bell pit' system was introduced. Here narrow shafts were sunk from the surface to the level of the deposits, and were then made as wide as was compatible with safety. The ore on being brought up was first washed on a coarse sieve, and was then subjected to a preliminary burning treatment known as 'elyng'. The ore was then ready for smelting.

For this process (although coal was by no means unknown) the chief fuel used was charcoal, mixed where available with peat. The crudest and oldest method was to choose a site exposed to winds and draughts and to set upon it a clay hearth. The ore would then be arranged in layers alternating with layers of charcoal, the whole being covered with clay to retain the heat, whilst holes would be provided at the base both in order to admit the draught of air for facilitating combustion and to provide an outlet for the molten ore. This method was, however, soon improved upon. Thus in place of the clay, a closed-in cylindrical stone furnace came to be employed. Attention, too, began to be directed towards improving the draught by the aid of foot and hand bellows (first invented during the fourth century). Later there were substituted for the foot bellows more effective ones driven by water-wheels. Improvements in furnace construction rapidly followed, and towards the end of the fifteenth century the blast-furnace was of the shape of a truncated cone some 24 feet in diameter at the base, and up to 30 feet high; at

the base was a cupped or bowl-shaped hearth of sandstone, and on this was laid as before alternate charges of fuel and ore, fed into the furnace from the top. As the pig iron was smelted out, it settled to the bottom of the bowl, and from this it was taken in a lump known as a 'sow'. Increased efficiency came still later with improved draughts, and from the higher temperatures thus obtainable in the sixteenth century cast iron began to be produced, the re-smelting of which was found to give a much better wrought iron than before.

In addition to this large-scale smelting, there were also in use smaller and cruder types of itinerant forges. These were in effect ordinary blacksmiths' forges at the bases of which were cupped crucibles for the reception of the molten iron. Of these it is recorded there were in the Forest of Dean alone as many as sixty in blast at the end of the thirteenth century, whilst many farmers had their own little forges from which they were able to produce for themselves the iron for their tools. Accompanying such itinerant forges, known as 'bloomeries', were usually 'smithies' of the ordinary kind. The two went together, so that the smallest iron product derived from the one could be purified and worked up by hammering at the other. The wood or charcoal served two purposes—to supply the heat and to deoxidize the ore. Its carbonizing effect, however, was so great that it would sometimes produce, instead of the malleable wrought iron, the relatively harder but more brittle natural steel, whilst at other times it would even produce a true cast iron whose extreme brittleness made it unworkable. As a matter of experience, the smith learned to separate out such specimens, and re-treat them by re-smelting with just the right amount of exposure to the blast necessary for burning out the excess of carbon. Similar but more elaborate treatment was accorded to the sows derived from the heavier type of processes. The sows were transferred from the furnace to the forge, known as a 'finery', and there hammered into an ingot of standard size (nearly 200 lb.)

known as a 'bloom'. The hammering was performed in smaller smithies by hand, but towards the end of the fifteenth century, water hammers, i.e. hammers worked by water-wheels, were installed in the larger 'fineries'.

It will be readily understood that the supply of fuel employed in iron-smelting was a serious consideration, and the charcoal-burners and wood-gatherers were in great demand. The consumption of wood, in particular, was enormous, and not until coal came to be successfully and generally employed (from about 1620 onwards) for iron smelting could the medieval era of iron production properly be regarded as having terminated.

III. LEAD, SILVER, AND TIN

Another technological industry of great consequence in the medieval period was that of lead mining and refining. In this England played a very important part, the mines of Alston Moor, Derbyshire, and the Mendips, which were worked from the earliest times, being a lucrative source for the world's general supply. By the twelfth century the output was very vigorous, and its importance was enhanced by the accompanying incidence of silver frequently associated with it. A lead mine, even on a very small scale, involved a considerable variety of labour; for in addition to the mine itself there was also a forge, worked by a man and a boy, a candle-maker, a carpenter, charcoal-burners and wood-cutters. Occasionally, too, the accumulation of water in the pits, sometimes very rapid, necessitated the employment of teams of men for the purpose of hand-bailing. In the early days of lead mining, indeed, the problem of pit drainage was one of great difficulty, and frequently it assumed such proportions as to render the closing down of the pits unavoidable. This was clearly an evil which urgently demanded a remedy, but it was not till 1297 that a solution came. The method was to drive a horizontal gallery, known as an 'adit' or 'avidod', from

the bottom of the pit shaft until it emerged to the open air on the slope at the top of which was the head of the shaft, and along this the water would flow as far as it could. Once the site of its outcrop was determined upon, the driving of the adit was a simple matter of proportion, solved by the comparison of similar triangles.

The economy of working derived from the utilization of this form of drainage was immediate in its effect. In one mine, for example, the yield in the year following its introduction was doubled, since work was now able to proceed in the winter months, where before this had been impossible.

The first operation involved in the handling of the lead and silver ore (spoken of as 'blackwork') after raising from the mine was that of breaking it up. At first this was done by hand with hammers, but during the sixteenth century mechanical stampers worked by water-wheels were introduced. The next operation was that of washing. The broken 'blackwork' was placed in a coarse sieve, and the stones and other impurities were removed as far as possible by shaking in 'buddles' or troughs. The washed ore was then ready for the smelting furnace.

Furnaces of three different types appear to have been in use during this period. The earliest was that known as a 'bole'. It was a rude stone structure resembling a lime kiln in appearance. An opening at the top served as a chimney and was also utilized for charging the furnace, whilst at the base were provided vents for the air blast. As with the earlier types of iron-smelting furnaces, these were built in exposed positions and depended upon the winds for the draught. The fuel used was brushwood. The bole was clearly a crude affair. It was unworkable in the absence of wind, and soon gave way to the 'slag hearth' type of furnace resembling a blacksmith's forge. This was provided with bellows, at first worked by hand or foot, but later (as early as 1295 in Devon and 1420 in Durham) by a water-wheel, and was a much more efficient affair. The

molten lead was received in the hollowed-out base of the hearth, and as this was burnt away by the heat rather rapidly it had to be constantly renewed. The fuel used for this type of furnace was chiefly charcoal, sometimes mixed with peat. In the later types, when water-wheels were introduced, these not only worked the bellows but also served to operate the mechanical crushers referred to above.

A third type of furnace, the 'turn hearth', appears to have been in use in the Mendip hills. It was probably a combination of the two previously described types, one portion of the hearth being adjustable to the direction of the wind—possibly a rotating shutter of some kind—whilst another opening was fixed and in the direction of the prevailing winds.

It should be understood that the lead thus far produced would generally contain a percentage of silver, and the next process was to separate this out. This was done by cupellation.

When a lead-silver alloy is melted on an open hearth freely exposed to the air, the lead is oxidized, producing the well-known litharge, and the silver is left. The litharge can either be skimmed off or made to be absorbed by the porous body of the hearth. The silver residue is not very pure, and the process is therefore repeated, more lead being added, and with each such repetition the silver becomes more and more refined.

As an absorbent medium for the hearth, bone ash was (and is) used, but in Devon the charred refuse of blocks of oak-bark, got from the medieval tanneries and known as 'tan turves', was employed in the form of a thick bed with a basin-like hollow in the middle. In this was placed the 'pig' of lead with its percentage of silver obtained from the smelting furnace, together with the fuel; after it melted, the fire was raked aside and a blast of air directed by means of bellows on to the exposed surface of the molten metal to produce oxidation. The degree of purity of the final silver product naturally

varied, and for minting purposes it would have to be alloyed in varying amounts so as to bring it up to the legal standards of those days.

In view of its great antiquity, no summary of the mining technology of the Middle Ages can be satisfactory which does not include an account of the mining of tin. We have already seen that the tin mines of Cornwall and Devon were working hundreds of years before the Christian era, and the early overseas trade with the Phoenicians and with Gaul was largely devoted to the export of tin, although, curiously enough, the Romans do not appear to have realized the full possibilities of English tin during their occupation. Indeed, there seems to have been, so far as England is concerned, a distinct lull in tin production, as there was with mining generally, until about the eleventh or twelfth century, from which time onwards there was once more a great activity in the workings of the mines.

Apart from differences due to the initial raising of the ore, the methods employed for tin were naturally very similar to those for lead. Tin deposits occur chiefly in veins embedded in the rock at varying depths. Occasionally these are found as outcrops on the banks of streams. In the course of time the forces of erosion and weathering play their parts in breaking away masses of stanniferous boulders which, being in their turn slowly broken up into smaller pieces, are carried onwards by the stream until they sink by their weight to form beds reaching to a thickness of many (sometimes as much as twenty) feet. Nowadays, of course, mines are sunk to the actual depths at which the veins naturally occur, but in the Middle Ages the workings were largely confined to the alluvial deposits in the streams, and to the larger boulder tin (known as 'shode') at the outcrop on the river banks, though more exceptionally the veins themselves were worked where these occurred near the surface. In such cases the usual method was to start with a trench and thence to proceed by steps or 'shammells' to increasing depths. Each shammell was the

platform upon which the miner would throw his ore from the lower trench. The bailing of water would require constant attention, of course, whilst later, with increased depth of working, the driving of avidods was probably customary. Little need be added as to the treatment of the ore thus raised. After breaking in troughs or 'buddles' for the removal of the lighter impurities, it was first melted down in a rough-and-ready open-air hearth. The resulting product was then transferred to the furnace proper, and as in the case of lead it was customary to cast the final product into blocks of standard size (100 lb. in Devon and 250 lb. in Cornwall).

IV. COAL

We conclude this chapter with a brief survey of the extent to which coal, that essential to modern industry, was employed in the Middle Ages. The idea is generally prevalent that coal was not known or used until comparatively modern times. This, however, is quite erroneous. It has been proved conclusively that in England the Romans were familiar with it and its uses. All along the famous Wall excavation has revealed not only the ash, but also stores, of unburnt coal. They probably used coal chiefly for the smelting of iron, but a reference to Solinus (*c.* third century A.D.) makes it probable that it was used as fuel for the sacred fire in the temple of Minerva at Bath. On the other hand, there is no suggestion that the Romans sank mines for coal. Their sources of supply would be confined almost entirely to outcrops.

As with so many other mining activities, the Saxon era is a blank so far as the use of coal is concerned. We find no further trace of its use until the late twelfth and the early thirteenth centuries. To distinguish it from a similar word implying charcoal, coal was usually spoken of as 'sea coal' (though sometimes as earth coal or quarry coal), probably from the fact that the first medieval supplies were those washed up by the sea,

or occurring as outcrop seams on the face of the cliffs. Sometimes it was spoken of as 'burning stone'.

In the Middle Ages coal was probably employed solely in connexion with smelting operations and in the burning of lime. Dwelling-houses had no chimneys, so that there could be no possibility of its domestic use. It is not surprising to hear of a street in London, Sea Coal Lane, being named after the chief activities of its residents, but it is particularly interesting to find the same street sometimes referred to as Lime Burners Lane as indicative of the connexion between the two acitivites.

The earliest coal workings were, as in the case of tin, shallow trenches dug where the coal was known to be near the surface, and early operations were probably carried on in Shropshire and in the Forest of Dean, at one place in which a tax of a penny per horse-load of coal was levied by the Constable of St. Briavels in his capacity of Warden of the Forest. Records of workings in the Midland Area (Derbyshire and Notts) date from 1257, in which year it is recorded that 'Queen Eleanor was driven from Nottingham Castle by the unpleasant fumes of the sea coal used in the busy town below'. Indeed, the smoke nuisance was such that in 1307 lime-burners in London were definitely forbidden to use sea coal.

During the thirteenth century the number of areas worked for coal in England rapidly increased, and by the end of the century most of the modern areas were being mined, whilst the open-cast system was beginning to give way to the bell-pit system already described in the case of iron mining. When the coal supply in one pit was exhausted, it was abandoned, and another sunk close to it after the old one had been filled in. Occasional neglect to fill up the disused pits gave rise to serious accidents, particularly if water accumulated within them, and cases are recorded of both men and cattle falling in and drowning.

As the workings got deeper, the methods of shafting

and drainage improved, adits being driven in as previously described.

Salzman, in his *English Industries in the Middle Ages*, gives the following vivid picture of the working of a pit in the fifteenth century:

'After the overseer had inspected the ground and chosen a likely place, a space was marked out and a small sum distributed among the workers as earnest money. The pit was then sunk at such charge as might be agreed upon: at Heworth in 1376 the charge was six shillings the fathom, at Griff in 1603 six shillings the ell. A small reward was paid when the vein of coal was struck, the pit was then cleaned up and timbered, and a water-gate or adit driven to afford drainage and ventilation. Over the mouth of the pit was erected a thatched hovel with wattled sides to keep the wind and rain from the pit, and in this was a windlass for raising the corves. The workmen consisted of hewers, who cut the coal, and bearers who carried it to the bottom of the pit and filled the corves. They were under the control of the "viewer" below ground and the "overman" at the surface.'

CHAPTER III

LEONARDO DA VINCI AND THE BEGINNINGS OF APPLIED MECHANICS

I. BIOGRAPHICAL DETAILS

OUR survey of the progress of engineering now brings us to the work of two great products of the Renaissance—Leonardo da Vinci, the founder of modern mechanical science, and Georgius Agricola, the founder of modern metallurgical science. These two sciences provide the theoretical bases for engineering processes and for the production of the materials of engineering practice, and their founders are therefore of considerable importance to the theme of this book. To each we will therefore devote a chapter.

Leonardo da Vinci (1452–1519), in particular, was a remarkable personality. Living as he did on the full crest of the wave of the Italian Remaissance, he practically embodied in himself the full expression of its manifold activities. Born near Florence, he was apprenticed at the age of fourteen to Andrea Verrocchio, a famous artist of those days. Verrocchio's tastes and, as a consequence, his circle of acquaintances were wide ; and from all these Leonardo developed a passion for scientific inquiry side by side with his development as an artist. At Florence in his early days he came under the influence of such men of science as Benedetto del' Abbaco, Giovanni Agiropulo, Leon Battista Alberti, and Toscanelli. In 1483 Leonardo migrated to Milan, where he took service under Ludovico Sforza in the capacity of

consulting engineer, architect and sculptor, and it is interesting to read the letter he wrote to Sforza in support of his application for this position. The letter gives us some idea of the wide technological claims of this brilliant man of genius, and in that respect fits in happily with our main theme. It reads as follows:

'Having, most illustrious sir, seen and considered the experiments of all those who profess to be masters in the art of invention of the apparatus of war, and having found that their instruments do not differ materially from those in general use, I venture, without wishing injury to anyone, to make known to your Excellency certain secrets of my own, briefly enumerated as follows:

'1. I have a process for the construction of very light bridges, capable of easy transport, by means of which the enemy may be put to flight and pursued; and of others more solid, which will resist both fire and sword, and which are easily lowered or raised. I know also of a means to burn and destroy hostile bridges.

'2. In case of the investment of a place, I know how to drain moats and construct scaling ladders and other such apparatus.

'3. Item; if, by reason of its elevation or strength, it is not possible to bombard a hostile position, I have a means of destruction by mining provided the foundations of the fortress are not of rock.

'4. I know also how to make light cannon easy of transport capable of ejecting inflammable matter, the smoke from which would cause terror, destruction and confusion among the enemy. (Note here a fifteenth-century anticipation of smoke screens and poison gas.)

'5. Item; by means of narrow and tortuous subterranean tunnels, dug without noise, I am able to create a passage to inaccessible places, even under rivers.

'6. Item; I know how to construct secure and covered wagons for the transport of guns into the enemy's lines, and not to be impeded by ever so dense a mass, and behind which the infantry can follow without danger. (A possible vision of the modern tank?)

'7. I can make cannon, mortars, and engines of fire, etc., of form both useful and beautiful, and different from those at present in use.

'8. Or if the use of cannon happens to be impracticable, I can replace them by catapults and other admirable projecting weapons at present unknown; in short, where such is the case I am able to devise endless means of attack.

'9. And, if the combat should be at sea, I have numerous, most powerful engines both for attack and defence; and ships

which are both gun-proof and fire-proof; and also powders and inflammables.

'10. In times of peace, I believe that I can compete with anyone in architecture, and in the construction of both public and private monuments, and in the building of canals.

'I am able to execute statues in marble, bronze, and clay; in painting, I can do as well as anyone else. In particular, I will undertake to execute the bronze horse in the eternal memory of your father and of the very illustrious house of Sforza, and if any of the above-mentioned things appear to you impossible or impracticable, I will offer to make an attempt at it in your park or in any other place which your Excellency may please to choose, to which I commend myself in all humility.'

Leonardo's stay in Milan ended in 1499 with the collapse of the power of Ludovico Sforza. His chief scientific friendship during this period was with Fra Luca Pacioli, the famous mathematician. For some years after we find da Vinci back again at Florence. In 1506, however, he accepted an invitation from Louis XII of France to return to Milan. He remained there till 1512, and later, in 1515, Francis I of France, Louis XII's successor, invited him to take up his residence in the castle of St. Cloud, near Amboise. Here he spent the remainder of his days. He died on May 2, 1519.

The reading of Leonardo da Vinci's manuscript has been a task of enormous difficulty, with which are honourably associated the names of a small band of enthusiastic students, chief among whom may be mentioned J. Paul Richter, G. Piumati and C. Ravaisson-Mollien. Leonardo, from the time he was twenty years of age onwards, invariably wrote in a manner calculated to confound his would-be readers. We may summarize the characteristics of his manuscript under four heads. (1) He wrote from right to left after the fashion of the Semitic group of languages; (2) his handwriting was of the kind known as 'mirrored', i.e. reversed in a manner such as would result from looking at a normal script in a mirror; (3) he employed an elaborate scheme of abbreviations; and (4) he omitted the use of punctuation. It is accordingly much to the credit of the patient workers to whom reference has been made above that,

in spite of these difficulties, the writings of this great genius of the Italian Renaissance have been rendered available to the world of science and letters generally.

It is only within comparatively recent years that the vast collection of notes and sketches accumulated by Leonardo da Vinci has been given the attention it deserves. Unfortunately circumstances were such that after his death they were lost sight of, and it was only after the lapse of centuries that they once again came to light. This loss was a serious misfortune to science. Leonardo's work was in itself so fruitful and varied, and his attitude to Nature so much more enlightened than that of those about him, that, if only those who followed after him could have had access to his writings and to his many anticipations of later discoveries in different fields of intellectual activity, there is no doubt that the course of scientific history would have been materially different in a number of important directions.

II. THE POSITION OF TECHNOLOGY IN THE FIFTEENTH CENTURY

During the first half of the Renaissance the awakening of science from its long slumber was only beginning. The true era of experimental and mechanical science came after the fifteenth century, and as is usual with the early histories of the various branches of the subject, the development was not initially a result of abstract inquiry but the outcome of the needs of the times. Consequently, fifteenth-century mechanical science was an empirical study of the applications to problems of navigation, military engineering, hydraulics, architecture and general technology.

So far as mechanics is concerned, the study of dynamics was practically unknown, whilst in statics very little advance had been made from the days of Aristotle and Archimedes.

The position of general technology in the fifteenth century does, however, call for further comment. Even

the most cursory glances through the pages of da Vinci's note-books suffice to show an amazing range of technological devices and machines of all conceivable kinds. However much these may have been the product of this great man's brains, it is impossible to believe that there was not in existence a tradition of technology from which Leonardo was able to draw a certain amount of inspiration. Such, indeed, there was. Konrad Kyeser, Johannes Fontana, Konrad Kauder, Jacopo Mariano, Hans Hartlieb, Francesco di Giorgio Martini and Roberto of Seldenbeck are only some amongst many technical writers of this period. Most or all of these had available for study the writings of such technological scientists of antiquity as Vitruvius, Heron, Ctestibus, and Pappus. Manuscripts of Vitruvius began to be available in print in the fifteenth century (they had been lost sight of since the tenth century, and were re-discovered by Poggio at St. Gall early in the fifteenth century). Leonardo frequently refers to this important writer, and his debt to Vitruvius was certainly very great. Among the fifteenth-century technologists Konrad Kyeser of Eichstaedt, in particular, left voluminous manuscripts early in the fifteenth century which were copied and re-copied many times, and became the standard work of his day on the subject.

There is very little doubt, then, that to some extent Leonardo da Vinci must have been indebted to Kyeser and his contemporaries for some, at any rate, of his technological inspiration. The fact remains, nevertheless, that in the main technology as da Vinci found it was largely an empirical study which had scarcely yet earned the name of an applied science. It would not, however, be right to assume from this that there was in the fifteenth century no such thing as mechanical science.

III. LEONARDO DA VINCI'S APPLIED MECHANICS

Leonardo very happily combined within himself those excellent qualities which produce both the theorist in

science and the technologist who blends his theory with practice, and what is equally important, his practice with theory.

Formal mechanics occupied a large part of his time and thought. Here, as in science generally, we find in Leonardo clear evidence of that spirit of independence and experimental inquiry which gave to Galileo, a hundred years after him, the title of ' Father of Experimental Science '. Galileo deserved this title, but it was accorded him in ignorance of the labours of da Vinci. It neither detracts from his glory nor does injustice to his forerunner, therefore, if we plead for Leonardo the corresponding title of ' Grandfather of Experimental Science '.

What, then, were his achievements in mechanics, the study to which he lovingly referred as ' the paradise of the mechanical sciences ' ? Virtually, we may say of him that he created the study of dynamics. He knew of the principle of inertia. He tells us that ' no body can move of itself, but by the action of some other, and that other is force ' ; of moving bodies, too, he tells us that ' all movement tends to maintenance ' ; whilst that he knew of the law of reactions is clear from his statement that ' an object offers as much resistance to the air as the air does to the object '.

Some of the most interesting of Leonardo's mechanical researches concern themselves with the principle of work. He did not, of course, use the term work. He did, however, appreciate the fact of a value in, and a measure of, what we may speak of as the achievement of a force. Thus he writes that ' if a force carries a weight in a certain time through a definite distance, the same force will carry half the body in the same time through double the path '. He recognized, in effect, a definite limit to the results for a given effort, and that this effort is not alone a question of the magnitude of the force, but also of the distance through which it acts. If the one be increased, it can only be at the expense of the other.

Intimately linked up with this principle of work was

the age-old myth of perpetual motion. If the principle of work be true, then the achievement of perpetual motion is impossible. On this matter Leonardo had no illusions whatever. There were, however, many contemporary with him who thought otherwise, and with these da Vinci had no patience. 'O speculators on perpetual motion,' he writes, 'how many vain projects of like character you have created! Go and be the companions of the searchers after gold.'

Leonardo's dynamics also included studies of motion down an inclined plane and the collision of bodies. But when we turn to statics, we find an even wider range of scientific activity on the part of our philosopher. We must remember, however, that here he was no longer treading on virgin soil. The works of Aristotle, Archimedes, Euclid, Heron, Pappus, and others during the Greek era, and of Jordanus Nemorarius, Albert of Saxony, and others in the Middle Ages, were known to him. On their foundation, however, he built very securely, and his notes show clearly and conclusively that he fully understood the lever principle, centres of gravity, a modified form of principle of moments, pulley systems and their mechanical advantage, and many other important branches of modern statics. We may sum up, in fact, by saying that the theoretical basis of his work in engineering and technology was not only sound but was in extent far ahead of his times.

A very striking proof of this is seen in those many notes which deal specifically with matters that figure in all courses of modern study in engineering under the heading of applied mechanics—problems of various mechanisms for the attainment of large mechanical advantages, toothed gearing for power transmission, investigations in the strengths of structures and loaded beams, friction, and so on. Let us consider his work in a few of these briefly.

Turning, then, to the various pulley systems with which Leonardo was familiar, we find that practically all forms of pulley combinations such as are met with in

the modern text-book are to be found in one place or another among his various manuscripts. Fig. 5 shows a typical example, with four fixed and four movable pulleys, and Leonardo reduces the discussion to the study of the tension in the rope. 'The weight divides itself into eight pieces of rope. The ninth opposed to this simply holds the equipoise of the eight.' A curious case is presented in one of his manuscripts by a note accompanying a sketch of a system of two fixed and two movable pulleys (Fig. 6). The load is twenty pounds, and the power should clearly be five pounds. Yet Leonardo makes it six pounds. His note reads :

FIG. 5.—Leonardo's Mechanics—A Simple Pulley System.

'If the burden borne be twenty pounds, then I say let ten pounds act on the pulley *l* and ten pounds on the pulley *k*, these being the points of suspension of the twenty pounds load.

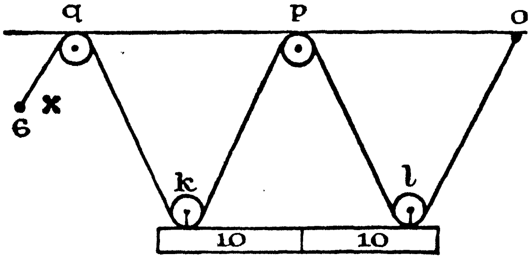


FIG. 6.—Leonardo's Mechanics—Effect of Friction on Mechanical Advantage.

That is to say, that *o* takes off from *l* five pounds, and *p* also takes five pounds from *l*, and five pounds from *k*. Finally *k* transmits five pounds to *q*. If one wishes to overcome the five pounds, one must apply at *x* an opposing weight of six pounds.

So long as one applies six pounds at the extreme point against the five pounds at *x*, and so long as each of the four pieces of string which bear the twenty pounds themselves only experience the five pounds pull, then because the active extra weight on the rope *q x* finds nothing to equal it in the opposing effective pieces of rope, the tension will be overcome, and movement will result.'

Clearly the point here is that whilst the theoretical value for the power is recognized by Leonardo as five pounds, nevertheless frictional and other resistances require an addition to this value in order that motion may ensue.

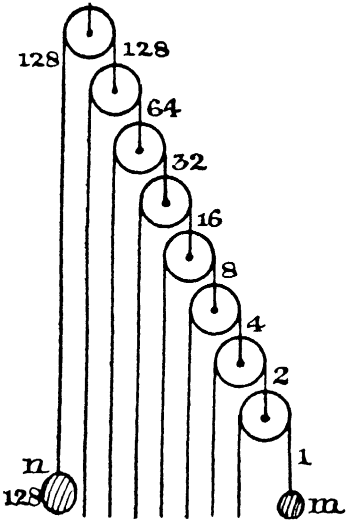


FIG. 7.—Leonardo's Mechanics—A Scheme of Movable Pulleys.

The use of sheaves of pulleys is frequently met with in da Vinci's manuscripts, whilst many other pulley systems are illustrated freely in the *Codex Atlanticus*. One such (Fig. 7) is of especial interest on account of the clear enunciation of the relationship between mechanical advantage and velocity ratio given in the text beside the drawing. It will be noticed that the figure, in so far as the scheme of tensions in the ropes and the relationship between power and load are concerned, is accurate and complete. The note reads:

'Just as one can here find a rule of diminishing force for the mover, so can one also lay down a rule for the increase in the velocity of the movement. The path of *m* stands in proportion to that of *n* as the weight *n* is to the weight *m*.'

Turning next to the transmission of power, we come again to a field which, by the fifteenth century, was already full of historical associations. Indeed, from the time when Aristotle had first discussed the gearing of three wheels in rough contact, the theory of power transmission, mainly through toothed gearing, progressed rapidly, to the accompaniment of an equally rapid development in practice. Hence, not only do we find innumerable examples of machines, structures, cranes, and all kinds of practical mechanism freely drawn and described throughout Leonardo's note-books, some of them indeed extremely elaborate and complicated in construction, but we also meet with a number of theoretical discussions. The ordinary cases of toothed wheels in gear with each other are naturally very frequent, but in addition Leonardo had a partiality for the method of transmission illustrated in Fig. 8, in which a wheel A is made to rotate by causing a number of pieces projecting from it at equal intervals to engage in the spaces between the cylindrical uprights of a rotating spindle B. By this means power is transmitted through a right angle.

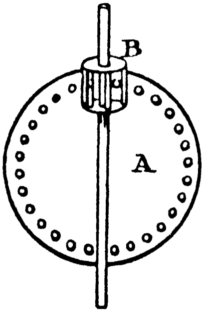


FIG. 8.—Simple Transmission of Power through a Right Angle.

The general scheme of Leonardo's theoretical treatment can perhaps be illustrated by a typical example (Fig. 9) taken from the *Codex Atlanticus*. The scheme is as follows: There are three large wheels, A, C and E, of which C and E are toothed. A has no teeth, but carries the power load at the extremity of a cord. The axles B, D and E of each of A, C and E are also toothed, and the radii of the axle wheels B and D are one-tenth of those of the larger wheels A and C, whilst that of F is *one-fifth* of E. F carries an endless chain along which the lifted load is distributed. Leonardo's treatment is

very simple, and is based entirely on the principle of the lever. He reduces the system to what he calls an 'interrupted balance', which is really a sequence of equivalent simple levers working from left to right as shown in Fig. 9A. In this we see that with a power of two pounds the system A B gives an equivalent load of twenty pounds, the system C D an equivalent load of 200 pounds, and E F a final load of 1,000 pounds.

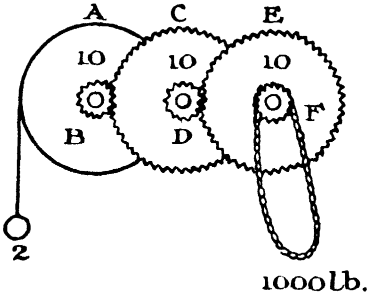
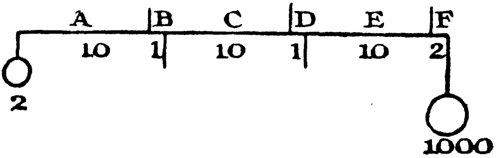


Fig. 9.—Leonardo's Design of Train of Toothed Wheels for Power Transmission with Large Mechanical Advantage.



9*a*.—His Calculation of Mechanical Advantage by method of "Interrupted Balance."

We turn next to another branch of inquiry in applied mechanics—that which belongs to-day to the strength of structures. Leonardo was again naturally interested as an engineer and an architect, but it was not alone in such rôles as these that he approached the subject. His study of bird flight also brought him into contact with this class of problem, and in his manuscript *On the Flight of Birds*, he asks: 'In which part of the under surface

of the width of the bird does the wing press the air more than in any other part of the length of the wings ?' So he begins with the consideration of a rigid structure supported at equal intervals.

'All bodies which do not bend', he says, 'will exert equal pressures on all the supports that are equally distant from the centre of gravity, the centre being the middle of the substance of such a body. One proves how the above-mentioned weight exerts equal pressure on its supports; let us assume that it is four pounds, and that it is sustained by the supports *a b*. I say that the body, being unhindered in its fall except by the two supports *a b*, these supports will sustain equal parts of this weight, that is to say, two and two.'

He then points out that this would not apply to the structure if it were not uniform. A similar example is to be seen in the *Codex Atlanticus*. A sketch shows a uniform beam of six pounds weight, and the reactions at the ends are given as three pounds each. Adjoining this, he next considers what happens when one support is moved inward two divisions (the beam has six equal divisions of length), and he correctly shows the reactions to be four and one-half and one and one-half pounds, respectively; and the problem is later expressed in more general terms by the assertion that if one support is kept unaltered at one end, and the other is moved towards it, the pull on the moved support steadily increases, whilst that on the fixed one equally diminishes. He gives a number of calculations in illustration of this, many of which are incorrect. Some, however, are quite correct, so that the errors are not due to faulty principles, but, as happens so frequently with da Vinci, to faulty mathematics.

Standing in a class by themselves are Leonardo's studies of the load which vertical struts, pillars, etc., are capable of sustaining. Most of his notes on this subject are to be found in Manuscript A of the collection at the Institute of France, though others also occur in the *Codex Atlanticus*, and they constitute the first scientific attempt of their kind. All previous efforts were frankly empirical. Of da Vinci's we can at least say that it

attempted scientifically to combine theory with practice. He begins early in the former manuscript by pointing out that a number of pillars or supports held together are stronger collectively than a single 'equivalent' pillar.

'Many little supports held together', i.e. in a bundle, he writes, 'are capable of bearing a greater load than if they are separated from each other. Of 1,000 such rushes of the same thickness and length which are separated from one another, each one will bend if you stick it upright and load it with a common weight. And if you bind them together with cords so that they touch each other, they will be able to carry a weight such that each single rush is in the position of supporting twelve times more weight than formerly.'

Later in the same manuscript he insists that this increase in the carrying capacity is entirely dependent upon the firmness with which the bundle is bound together, so that if the connexion is loose, the total load possible becomes merely equal to the sum of the loads of which each rush is separately capable, instead of a multiple of that sum.

It is interesting to note the nature of the experiments carried out by Leonardo in verification of the above. He applies a vertical load on a tightened iron wire strip, and increases the load until a plumb line indicates that the wire is beginning to bend. He then repeats the experiment with two wires bound together, and then with three, and so on. We quote his own words:

'Make the following experiment: Take two pieces of iron wire which have been stretched in a four-cornered wire drawer, and fasten one of them from below with two supports, and load it above a given weight. Notice exactly when it begins to incline, and further investigate with a thread which carries a plumb at which weight this inclination occurs. Next, double the iron wire, bind the two with a fine silk cord, and see whether this investigation agrees with what I have maintained. And similarly repeat the experiment with a fourfold increase, and so often as desired, continuing to bind the new ones with silk.'

We conclude our study of Leonardo's researches in applied mechanics with a note as to his experiments on friction. Here, undoubtedly, the experimental scientist

in da Vinci showed himself with distinction. It is regrettable that his work was lost to posterity. It was incomplete, and in some respects incorrect. But Amontons in 1699 and Coulomb after him had to cover much the same ground through ignorance of his work, where otherwise they might have gone much farther than they did. Leonardo's writings on friction are almost exclusively to be found in the *Codex Atlanticus.* His experiments were similar in scope to those of to-day —the sliding of a given surface over both horizontal and inclined planes by means of a weight passing over a pulley; and he carefully distinguished between sliding friction and rolling friction (' which, moving forward by infinitely small steps, touches rather than rubs ').

Leonardo's experiments led him to conclude that the amount of friction was independent of the areas of the surfaces in contact; that artificial smoothing or lubricating reduces friction; that for bodies polished or smoothed to an equal degree, the friction is proportional to the pressure between them, and that on a horizontal polished surface, the resistance to friction by all bodies is with a force equal to one-quarter of the weight. This last result is most interesting. It recognizes a definite coefficient of friction, but with a value common to all bodies and equal to 0·25. Nevertheless, in the general importance of the conclusions as a whole—since they afford us the first presentation in scientific history of any laws of friction whatever—we may well excuse Leonardo this incorrect result.

IV. LEONARDO DA VINCI'S TECHNOLOGY

Turning to the technology and engineering of Leonardo da Vinci, we may say at once that his notes cover a range which almost beggars description. Designs of almost every conceivable kind of machine required for every conceivable kind of technological process are scattered liberally through his manuscripts. Planing machines, filing machines, polishing machines, grinding

machines, lathes, mechanical hammers, wire-drawing machines, oil presses, screw-cutting machines, designs for roller bearings, needle-manufacturing machines, spinning machines, machines for rope making and cloth shearing, pumps, cranes, jacks, and other lifting gear, water-wheels, designs for irrigation and drainage, the cutting of canals, the erection of harbours and docks, and the design of cannons and other weapons and engines of war—all these interested our philosopher and prompted him to write notes and draw sketches and designs.

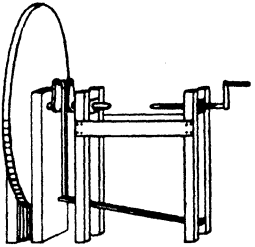


FIG. 10.—Leonardo's Treadle Lathe.

Obviously this book is not the place for a due consideration of this astonishing output, but as illustration of some of the mechanisms of the late fifteenth and early sixteenth centuries we proceed to describe a select few of Leonardo's designs. We begin with this sketch of a single treadle lathe (Fig. 10), the chief feature of which is the addition of a fly-wheel. This of course, operated as a steadying influence on the working of the machine and was a fairly new device. In the next figure (Fig. 11) we see an example of what Leonardo called a 'double lifting jack'. The diagram is practically self-explanatory, and we see a 1,000-lb. load being lifted by a rack-and-pinion mechanism. More pretentious,

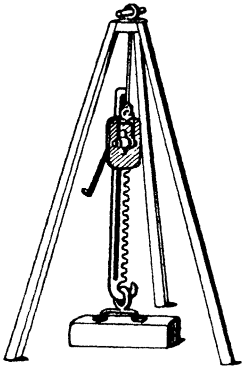


FIG. 11. — Leonardo's Rack and Pinion Device for Raising Loads.

however, is the vertical travelling crane next shown (Fig. 12), used for the erection of tall columns. The lifting mechanism itself is clearly indicated in the illustration, whilst above is seen the guide ropes along which the crane moves by means of the small trolley below.

Fig. 13 shows a design of an oil press. The olives are contained in two press-baskets, the lower one fixed and the upper one held by a screw operated through a suitable gearing to the power applied at the extremity of the long handle. A receptacle below the baskets catches the escaping oil. Hand power is first applied, and horse power is then brought to bear upon it. Leonardo describes the working thus:

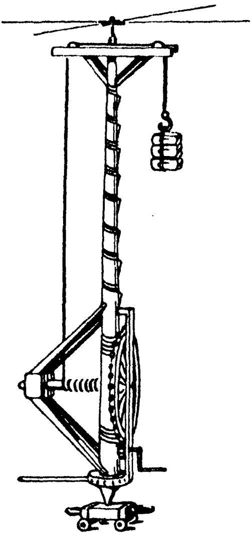


FIG. 12.—Leonardo's Design for a Travelling Crane.

'Each time you wish to give the screw a direct turn take away the transverse which is above the press-baskets, and turn the screw in such a manner that you press the two baskets as firmly together as possible. Then you replace the transverse, tie a horse to the large lever, and let it go round; I promise you that the olives will be pressed so firmly that they will look as if they are dried. But understand that such a press will have to be made much stronger than the others which are in use, in order that it may not be overpowered by the strength of the horse, but will withstand a sufficient resistance.'

Finally, in Fig. 14 we see an example of a polishing machine. The figure shows a rough sketch from Leonardo's note-books of a design for the grinding and polishing of hollow cylinders. It contains one or two ingenious features. The hollow cylinder is held fast

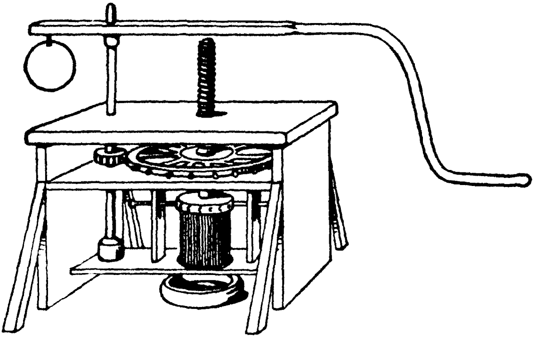


FIG. 13.—Leonardo's Oil Press.

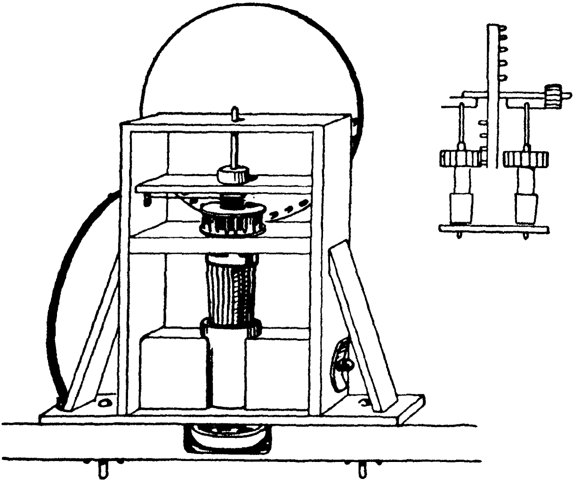


FIG. 14.—Leonardo's Design for Grinding and Polishing Hollow Cylinders.

by two cheeks, one on each side, each being clamped securely to the wall of the large bracket by a nut and

bolt. Filling out the interior of the hollow cylinder are shaped blocks of wood, down the channels and gaps between and around which are poured a mixture of oil and emery. The upper extremity of the projecting blocks of wood is held in the base of a screw which is prevented from rotating by a rectangualr iron block, through which it passes to receive a nut. The nut is free to rotate, but not to move up and down. The screw is free to move up or down, but not to rotate. Consequently, when the nut is made to rotate, the screw, and therefore the blocks within the cylinder, move up and down. The purpose of the mechanism is to create periodic reverses in the direction of rotation of the nut, by causing the blocks to move alternately up and down, and so to grind the inside surface of the cylindrical specimen. The device for ensuring this is distinctly ingenious. The nut carries a rack wheel which engages in the teeth. At the same time above the small horizontal wheel of the nut we have a piece of string wound round, the end being carried to the top of a perpendicularly fixed spring coming from the base board to the left of the long one. The apparatus now works as follows. The operator turns the large wheel through half a circle, during which the nut engaging with it will rotate a few revolutions, thus at the same time both winding the string (and therefore pulling back the spring) and causing the wooden blocks to move up. The larger wheel is now let go, and the rebound of the spring at once asserts itself. The string unwinds and the previous motion is reversed. The operation is thus repeated indefinitely, the escaping mixture of oil and emery being caught in a receptacle provided below.

It is interesting to note that in the top right-hand corner of the illustration Leonardo develops the idea still further, so that, by providing the top half of the larger wheel on the opposite side with another set of teeth, he is able to operate two machines at the same time, so that when one set of grinding blocks moves up, the other set moves down, and vice versa.

CHAPTER IV

GEORGIUS AGRICOLA AND THE RISE OF METALLURGICAL SCIENCE

I. INTRODUCTION

IN the last chapter we saw how, under the skilful guidance of the great genius of the Italian Renaissance, Leonardo da Vinci, the mechanical sciences not only began to take modern shape, but also to find a practical application to machinery. Appliances and gear for hauling loads, for the transmission of power, for the easier manufacture of implements and for general daily requirements, both in peace and war, came to be more easily and effectively made. The lathe, the boring machine, cutting tools and the like, although still crude in design and performance as modern standards go, were nevertheless undergoing improvement. Having regard to the limitations imposed by the absence of steam power, the stimulus to the mechanical processes of the late fifteenth and early sixteenth centuries was indeed a real one.

Side by side with this advance, we have now to consider a corresponding advance in the science of metallurgy that carried in its wake an increased efficiency in the processes of mining technology, and thus provided the great engineers with the materials for their lifework. These two phases of industrial activity, mechanical technology and the industry of mining, were then, as they are now, closely related to one another. On the one hand the improvement in machinery effected a

greater efficiency in the working of the mines through the better plant which could thereby be installed, while on the other hand the mines, through their better working, gave an increased stimulus to the study of iron and steel and other metal products, and so made possible yet further advances in the improvement of the qualities and strength of the materials of machinery manufacture.

Just as Leonardo da Vinci was the great figure in the inauguration of mechanical and engineering science, so was Georgius Agricola the central figure in the sixteenth century birth of metallurgical science and in the resulting production of the materials for the engineer. The times were ripe for progress. The spirit of adventure was abroad. The great geographical discoveries of Columbus and his contemporaries filled Europe with wonder, and fired the imaginations of all thinking men. Leisure for thought was also increasing as a result of commercial prosperity. In Germany, the Hanseatic League was monopolizing the trade of the north, whilst in the south there were close commerical relations with Italy. In this latter country, in spite of continual warfare, such towns as Venice and Florence were prospering commercially, so that more time was available for cultural development, in the furtherance of which we need scarcely stress the importance of the advent of printing.

All this naturally found its reflex in applied acience. The opening up of South America through the energies of the maritime adventurers of Western Europe quickly showed vast potentialities of wealth in the immense ore deposits that were speedily found. There was every stimulus to the scientific study of metals and their ores, and only the right type of investigator was wanting to set things going. Such a person was Georgius Agricola, whose life and work it is our purpose to survey.

II. GEORGIUS AGRICOLA (1494–1555)

Georgius Agricola is the latinized name (in conformity with the usual practice of those times) of Georg Bauer. We know very little of either his parentage or his youth. He was born at Glauchau, in Saxony, on March 24, 1494, at a significant period in the world's history. Luther was born just one year earlier, and Erasmus, who was later to become his friend and patron, was yet a student. Columbus had just returned from his epoch-making voyage of discovery, whilst three years earlier Vasco da Gama had rounded the Cape of Good Hope. By the time Agricola was beginning his university career as a student at Leipsic at the age of twenty, Balboa had already seen the Pacific for the first time, and by 1520 Cortes had entered the city of Mexico.

Agricola's education was as thorough as the times permitted. His studies embraced the classics, philosophy and medicine, and he was clearly a most avid reader and sincere scholar. He graduated at Leipsic in 1518 and was at once appointed Vice-Principal of the Municipal School at Zwickau. Here he taught Latin and Greek and published a small Latin Grammar. Two years later he became Principal. In 1522 he accepted the appointment of lecturer at his old university at Leipsic, but he did not stay long. The natural centre for intensive study of philosophy, medicine and natural science was Italy, which had now reached the summit of its Renaissance, and here he journeyed from 1522 to 1524, visiting a number of universities in turn. It was under the inspiration of these institutions that he began his first scientific work, a revision of Galen. It was about this time, too, that he first met Erasmus, who was now an editor at Basel for Froben's press.

Agricola returned to Zwickau in 1526 to take up the profession of medicine, and a year later he moved to Joachimsthal, a small Bohemian town on the eastern slope of the Erzgebirge, where he was appointed the

town physician. It was here that he began those metallurgical studies that were to make him famous. Joachimsthal was situated right in the heart of the metal-bearing areas of Central Europe. It was itself a thriving little mining city. Agricola's work brought him into constant contact with this occupation, and he speedily became sufficiently interested to make a study of it. In 1530 he wrote his first work on the subject, *Bermannus*, a book which took its name from Lornz Berman, a miner friend.

Bermannus was a general work on mineralogy and mining lore, and its publication was due to the efforts of Erasmus, who had by now become greatly interested in Agricola's career. This was followed up in 1533 by a treatise on Roman and Greek weights and measures, *De Mensuris et Ponderibus*. It was shortly after this that Agricola began his most famous work, *De Re Metallica*, though it was to be many years before this book was published. Agricola had by now moved to the city of Chemnitz, where he became the city physician, and here he remained until his death in 1555. All his leisure was given to the study of metallurgical science. In 1543 he married Anna (probably his second wife), widow of a Civil servant, by whom he had several children.

The most active period of Agricola's literary work began in 1544, and his works included *De Ortu et Causis Subterraneorum*, a work on physical geology ; *De Natura Eorum quae Effluunt ex Terra*, a book on subterranean waters and gases ; *De Natura Fossilium*, a work on mineralogy, and several others. The *De Re Metallica* was probably completed in 1550, but it was not in fact published until 1556, the year after his death.

It is a curious commentary on the people amongst whom he lived that for this man, whose work brought so much prosperity to them, so little has been done to perpetuate his memory. A brass memorial plate which was hung in the cathedral at Zeitz had disappeared by 1686, and little now remains to commemorate the work

and life of this great pioneer of theoretical and applied science, with the exception of a marble tablet now housed in the historical museum at Chemnitz.

III. *DE RE METALLICA*

We have mentioned that Agricola spent some twenty years in the preparation of this great work. The fact that it was being written was well known, and in view of his wide reputation, it was undoubtedly looked forward to with eagerness by the intellectual world of his day. Thus his friend George Fabricius wrote to a friend: 'With great excitement the books *De Re Metallica* are being awaited. If he treats the material at hand with his usual zeal he will win for himself glory such as no one in any of the fields of literature has attained for the last one thousand years.' The work was finished by 1550, but its publication was long delayed on account of the preparation of the many elaborate woodcuts with which it was to be illustrated. By 1553 all was ready, and the book was sent to Froben for publication. It was, of course, written in Latin. A very fine translation, with detailed commentary, was undertaken and completed in English by Messrs. H. C. and L. H. Hoover, and was published in 1912, and most of the material for this chapter has been taken from it.

The *De Re Metallica* is made up of twelve books or parts. We can best summarize the scope of the work by quoting the following extract from Agricola's preface:

'. . . I have written these twelve books, *De Re Metallica*. Of these the first book contains the arguments which may be used against this art and against metals and the mines. The second book describes the miner and branches into a discourse on the founding of veins, the third book deals with veins and stringers and seams in the rocks. The fourth book explains the method of delimiting veins, and also describes the functions of the mining officials. The fifth book describes the digging of ore and the surveyor's art. The sixth book describes the miners' tools and machines, the seventh book is on the assaying of ore. The eighth book lays down the rules for the work of roasting, crushing and washing the ore. The ninth book explains the

methods of smelting ores. The tenth book instructs those who are studious of the metallic arts in the work of separating silver from gold, and lead from gold and silver. The eleventh book shows the way of separating silver from copper. The twelfth book gives us rules for manufacturing salt, soda, allum, vitriol, sulphur, bitumen, and glass.'

This summary gives us but a faint and inadequate picture of the thoroughness of his treatment. The value of the work extends, however, far beyond the mere confines of metallurgical science. To the student of scientific history it offers the most valuable possible picture of the degree to which practical mathematics and applied mechanics had by the sixteenth century become the handmaidens of technology. Thus Book V, which is devoted to the principles of underground mining and the art of surveying, shows both in text and illustration how the mathematics of those days was applied to the scientific layout of a mine. It includes, by way of explanation, a summary of the mathematics of the triangle, and it describes in detail the various surveying instruments used in connexion therewith.

Again, in Book VI we have a complete account of the tools and machinery of the sixteenth century given in connexion with current methods of winding, ventilating and pumping machinery. The whole subject of the transmission of power by block and pulley, the windlass, the use of water-wheels, and of the shafts of gear-wheels, the types of chain pumps and of piston pumps with valves are all here collected and described. It is not claimed that Agricola contributed here anything that was new. But he did collate facts in the most thorough manner conceivable, and so presents to us a picture of the applied mechanics of his times. Also by bringing to the notice of his contemporaries in this complete form a knowledge of all that was possible, he provided a stimulus to the further study of mechanical sciences. It is impossible within the limits of these few pages to do more than barely mention the scope of this chapter. He begins by describing the various hand-tools and their construction—the hammer, the pick, the hoe, the shovel,

etc. He then proceeds to describe various kinds of buckets, wheelbarrows, and trucks. Various kinds of holding gear next engaged his attention, each machine he describes being more complicated in details than the preceding one.

In Book VII we come to the business proper of the experimental metallurgists, namely the theory and practice of assaying. The purpose of this section is stated very clearly by Agricola in the following terms:

> 'By tests of this kind miners can determine with certainty whether ores are contained in the metal or not; or if it has already been indicated that the ore contains one or more metals, the tests show whether it is much or little; the miners also ascertain by such tests the method by which the metal can be separated from that part of the ore devoid of it; and further by these tests they determine that part in which there is much metal from that part in which there is little. Unless these tests have been carefully applied before the metals are melted out, the ore cannot be smelted without great loss to the owners, for the parts which do not easily melt in the fire carry the metals off with them or consume them.'

These very explicit statements show clearly the scope and purpose of this section of the work. Nevertheless it must not be assumed that Agricola was the first assayer. The practice of assaying was undoubtedly of steady growth. We have seen, however, how very jumbled had been the previous writings on the subject, and what can pertinently be claimed for Agricola was that his was easily the most scientific exposition of the whole subject, and that because of this the would-be student was able to read with understanding, and to derive from *De Re Metallica* that inspiration for further study and experiment which is one of the true requisites of scientific progress. Actually the assaying of gold and silver had been developed to a considerable extent by his alchemistic predecessors. The scientific assaying, however, of lead, copper, tin, quicksilver, iron and bismuth was almost wholly new, and as such provided a remarkable contribution to the subject.

Agricola begins early in Book VII with a description

of the assaying furnace. He follows this up with the construction and use of the hand-bellows and then proceeds to an account of the various types of muffles, crucibles, and cupels in general use. He then proceeds:

'I will now speak of the preparation of the ore for assaying. It is prepared by roasting, burning, crushing and washing. It is necessary to take a fixed weight of ore in order that one may determine how great a proportion of it these preparations consume. The hard stone containing the metal is burned in order that, when this hardness has been overcome, it can be crushed and washed; indeed, the very hardest before it is burned is sprinkled with vinegar, in order that it may more rapidly soften in the fire. The soft stone should be broken with a hammer, crushed in a mortar and reduced to powder; then it should be washed and then dried again. If earth is mixed with the mineral it is washed in a basin, and that which settles is assayed in the fire after it is dried. All mining products which are washed must again be dried. But ore which is rich in metal is neither burnt nor crushed nor washed, but is roasted, lest that method of preparation should lose some of the metal. When the fires have been kindled this kind of ore is roasted in an enclosed pot which is stopped up with lute.'

Agricola now passes to the subject of fluxes. Here again we cannot do better than let him speak for himself:

'I have decided to explain those things which mining people usually call fluxes, because they are added to ores, not only for assaying, but also for smelting. Great power is discovered in all these fluxes . . . and some are of a very complicated nature. For when they have been mixed with the ore and are melted in either the assay or the smelting furnace, some of them, because they melt easily, to some extent melt the ore; others, because they either make the ore very hot or penetrate into it, greatly assist the fire in separating the impurities from the metals, and they also mix the fused part with the lead, or they partly protect from the fire the ore whose metal contents would be either consumed in the fire or carried up with the fumes and fly out of the furnace; some fluxes absorb the metals.'

Agricola then goes into details regarding these various types of fluxes, after which he comments on the colour of the fumes as an indicator of the type of flux necessary:

'The colour of the fumes which the ores emits after being placed on a hot shovel or an iron plate indicates what flux is needed in addition to the lead, for the purpose of either assay-

ing or smelting. If the fumes have a purple tint, it is best of all, and the ore does not generally require any flux whatever. If the fumes are blue, there should be added cakes melted out of pyrites or other cupriferous rocks; if yellow, litharge and sulphur should be added; if red, glass-galls and salt; if green, then cakes melted from cupriferous stones, litharge and glass-galls' . . . and so on.

He is now ready to describe the carrying out of a typical assay:

'In the assay furnace, when it has been prepared in the way in which I have described, is first placed a muffle. Then selected pieces of live charcoals are laid on it, for, from pieces of inferior quality a great quantity of ash collects around the muffle and hinders the action of the fire. Then the scorifiers (crucibles) are placed under the muffle with tongs, and glowing coals are placed in the forepart of the muffle to warm the scorifiers more equally; and when the lead or ore is to be placed in the scorifiers they are taken out again with the tongs. When the scorifiers glow in the heat, first of all the ash or small charcoals, if any have fallen into them, should be blown away with an iron pipe two feet long and a digit in diameter; this same thing must be done if ash or small coal has fallen into the cupels. Next, put in a small ball of lead with the tongs, and when this lead has begun to be burnt into fumes and consumed, add to it the prepared ore wrapped in paper. It is preferable with the assayer to wrap it in paper, and in this way put it in the scorifier, than that he should drop it in with a copper ladle; for when the scorifiers are small, if he uses the ladle, he frequently spills some part of the ore. When the paper is burnt he stirs the ore with the small charcoal held in the tongs so that the lead may absorb the metal which is mixed with the ore; when this mixture has taken place the slag partly adheres by its circumference to the scorifiers and makes a kind of black ring, and partly floats on the lead in which is mixed the gold and silver; then the slag must be removed from it . . . when the heat of the fire has nearly consumed the lead, then is the time when the gold and silver gleam in their varied colours, and when all the lead has been consumed the gold or silver settles in the cupel. Then as soon as possible remove the cupel out of the furnace, and take the button out of it while it is still warm, in order that it does not adhere to the ashes. This generally happens if the button is already cold when it is taken out. If the ashes do adhere to it do not scrape it with a knife lest some of it be lost and the assay be erroneous, but squeeze it with the iron tongues so that the ashes drop off with the pressure. Finally it is of advantage to make two or three assays of the same ore at the same time,

in order that if by any chance one is not successful, the second, or in any event the third, may be certain.'

We do not pretend that the above extracts give anything like a true picture of all that is to be found in this great work. They are but examples illustrative of the care and clarity of the exposition, and of the scientific instincts of their author. The remaining Books VIII to XII are taken up with the applications of the study of assaying to the actual practice of mining in all its many phases—the selection of ores, their sorting, breaking, crushing, grinding, washing, etc., the various smelting processes, and the separating of two or more metals when melted out of the same ore (e.g. the parting of gold from silver and of silver from copper, and so on).

IV. CONCLUSION

It will be clear from what we have said in the previous sections of this chapter that Georgius Agricola must undoubtedly be reckoned one of the great pioneers of industrial science. Equipped as we have seen him to have been with an education as broad as it was possible for him to have, and with the added advantages of travel and contact with the political and industrial activities of his times, he exerted an influence which was both real and profound. The narrow outlook of the scholastics made no appeal to him, and he was fundamentally a teacher of the experimental school. It must not be supposed, on the other hand, that he was entirely free from the prejudices or superstitions current in his day. For example, he believed in the existence of good and evil spirits, both down the mine and elsewhere. On the whole, however, his outlook was sane, healthy and constructive. He contributed definitely to geological theory, and in his *De Ortu et Causis* we find one of the earliest definitions of the part played by erosion in the making of landscape. Much interest, too, centres round his views on the origin of ore deposits and his contentions as to the part played therein by the circulation of ground

waters. Agricola held that ore channels are subsequent to the contained rocks, and that these channels were filled by exposition from running water suitably charged with matter in solution. In mineralogy, too, Agricola was a pioneer. He had, of course, little in the way of chemical knowledge to go upon, other than such properties as solubility and homogeneity, and upon physical qualities such as colour and hardness. Nevertheless, he contributed to the existing list of mineral species some score of fresh ones.

This, then, is the account of what may be regarded as the inauguration of the modern era of metallurgy. We have only to look around and to remember the vast extent to which the world of engineering is dependent upon the scientific production of the metals which form the basis for all its processes and activities, and we see at once how important must have been the work of one who, relieving mankind from the dilatory methods and ignorance of a medieval past, could substitute for them the basis for a sound theoretical knowledge and efficient technological practice.

CHAPTER V

THE EARLY PIONEERS OF THE STEAM ENGINE

I. INTRODUCTION

SO largely was the rapid growth of eighteenth- and nineteenth-century industrialism the direct outcome of the applications of mechanical power to production and distribution, and so vast was the revolution in engineering practice brought about by the advent of the steam engine, that in many respects it is pertinent to regard the invention of this engine as the pivotal point in the history of industrial science. Accordingly James Watt must always be given a prominent place in the story of mankind as a benefactor of civilization, and in due course the record of his inventions will begin in these pages. We must remember, however, that a certain measure of pioneer work preceded Watt, and laid the foundations of his great discovery. Our first task, therefore, is to consider this pioneer work, and to trace the development of the steam engine from its earliest beginnings.

The story carries us back a long way into the past. In the famous *Pneumatica*, much of the materials for which Heron derived from Ctesibius, we find a number of examples of the earliest germs of both the steam and hot-air engine. In both of these the principle of expansion on heating was known, and the force of the expansion was utilized. The *Pneumatica* is built up in the form of a series of propositions. One of the best

known of these, No. 70, describes the device known as the *Aeolipile,* or Ball of Æolus (Fig. 15). A portable cauldron A, mounted on claw legs, contains water, and is provided with a steam-tight cover B. Projecting from the cauldron are two tubes CD and EF, provided with right-angle bends at the top. These carry the ball G, the extremity D of the pipe CD forming a pivot point, whilst the other extremity F of EF opens directly into G. At extremities of the vertical diameter of the ball are two short open tubes H and K projecting from the ball. These are provided with right-angled bends in opposite directions. A fire is lit beneath the cauldron, and in due course steam is formed and is forced up the only exit EF from the cauldron into the ball G, and thence escapes to the air through H and K. The unbalanced couple thus produced sets up by reaction a rotation of G about the axis DF in a direction opposite to that of the issuing streams of steam. In effect we have here in its crudest form the principle of the steam turbine; yet many centuries were to pass before this principle found active employment in useful practice. The ancients, then, knew something of steam and hot air; but they did not realize the possibilities involved. They regarded them rather as instruments for spectacular pleasure—for the construction of large-scale toys. Afterwards the few who might have

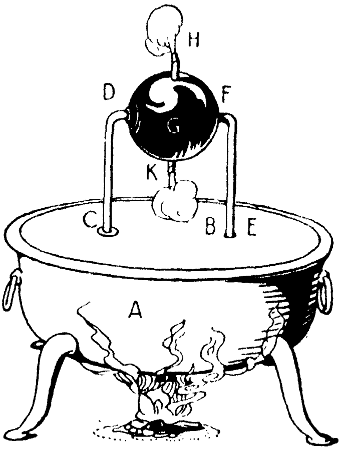


FIG. 15.—Heron's Aeolipile.

known of the Greek toys were not of the mentality or outlook to apply the basic ideas underlying them to something of more practical utility, and, accordingly, we hear little more of the possibilities of hot air and steam for many hundreds of years.

II. THE FIFTEENTH AND SIXTEENTH CENTURIES

So we come to the fifteenth century, and in view of what we have said in Chapter III, it will not be surprising to the reader that the great scientist of the Italian Renaissance, Leonardo da Vinci, gave some attention to the subject. Characteristically, not only did he realize something of the power of steam, but he also attempted a quantitative experiment on its expansion. His apparatus was simple. What to-day we would call a rectangular calorimeter (Fig. 16) containing water A was fitted with a cover B (acting like a piston). This cover was held in position over the liquid by a counterweight C suspended from a cord passing over pulleys. By means of a fire D under A, the water was heated until steam was formed, and the expansion of this steam forced the cover B up to some fresh position B′. Leonardo then proposed to measure the amount x of this expansion and compared it with the original height y of B above the base of the vessel.

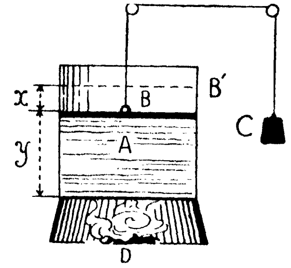


FIG. 16.—Leonardo's Experiment on the Power of Steam.

A very interesting sixteenth-century reference next claims our attention. In 1543 Blasco de Garay, a master mariner, was reputed to have carried out experiments with a view to the mechanical propulsion of vessels. According to one account, 'the spectators saw

that it principally consisted of an apparatus for boiling a great quantity of water, in certain wheels which served as oars, and a machine which communicated to them the *steam* produced by the boiling water'. Garay certainly received official recognition. In so far as he succeeded by this means in towing a ship out of port (at the rate of about one league per hour) and in keeping the ship under proper control, the experiment was apparently a success. Garay, in his desire to maintain secrecy as to his invention, carefully removed from the ship all trace of his machinery. The experiment, through a variety of circumstances, was not repeated, and so the truth was lost to posterity.

Although there is little left to record of the actual steam engine in the sixteenth century, we now come to a period of great significance in the study of applied mechanics and mechanisms.

The new spirit, emanating from Germany through the influences of Agricola, soon became transmitted to France, and here Jacob Besson, who taught natural philosophy at Orleans, and Agostino Ramelli, an Italian philosopher of versatile interests who had migrated to Paris, soon came to the fore. Besson's *Theatrum Instrumentorum et Machinarum* was published in 1578, whilst Ramelli's *Le diverse et artifiore machine* was issued ten years later. Both dealt fully and scientifically with the whole subject of the applications of mechanics to mechanisms and machinery, whilst Besson's book included a study of the production and properties of steam. Both works became standards of reference for subsequent writers for a long time.

III. THE BEGINNING OF THE SEVENTEENTH CENTURY

The new century immediately showed results from the work of preparation of the previous century. Living in Naples at that time was a gifted student and philosopher named Giovanni Battista della Porta. He was a

well-known and popular figure in the intellectual circles of his native city. Of an inventive turn of mind, he was very much interested in Heron's *Pneumatica*, the reading of which inspired him to experiments and to the design of mechanisms of considerable ingenuity. These he published in 1601 in the form of a commentary on Heron's work under the title of *Pneumaticorum libri tres*, and in the course of this work he described a machine for raising water based on the steam fountain of Heron that we have already discussed. Instead, however, of using hot air, Porta used steam. The scheme of his experiment is illustrated in Fig. 17. A retort A contains water, and a tube B leads from it into a tank C fitted with a plug D. Issuing from the tank is a delivery tube E. The action is perfectly simple. By means of a furnace F beneath A, steam is produced and delivered to the air space above the water in the tank C. The pressure on the surface of the water is transmitted through the liquid and a stream is forced up the tube E. It is interesting to note, too, that della Porta was alive to the possibilities of reduced pressure by condensation, and to the obtaining of an inflow of water from a lower level into the partial vacuum thus produced by the pressure of the external atmosphere. We shall see later that Savery, a hundred years after, utilized almost the same ideas to produce what was virtually the first successful steam engine of commercial utility.

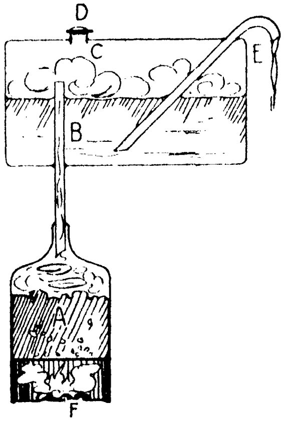


FIG. 17.—della Porta's Apparatus for Raising Water by Steam Power.

As a break from the continuity of this line of development, we have next to draw attention to the work of an Italian engineer named Giovanni Branca, a native of Loretto. In 1629 he published at Rome a book, entitled *Le machine diverse del Signior Giovanni*, which was characterized by a relatively high standard of attainment from the point of view of mechanisms reminiscent of the earlier French school of Besson and Ramelli. Whatever else may be said of his proposals regarding the steam engine, we may at least claim for them that they introduced the element of utility hitherto absent, except possibly in the case of de Garay's experiment. His scheme, as shown in Fig. 18, is that of the impinging of a jet of steam from a boiler designed in the figure of a man (note the filling plug on the man's head) on to a horizontal wheel fitted with vanes. By suitable mechanism this is made to gear with a horizontal drum, and the power thus transmitted is applied to a variety of useful purposes—e.g. in the figure, to the mechanical stirring of the ingredients in the bowls at the base of the apparatus. The germs of the steam turbine are here, but at the time the idea was incapable of development. Indeed, it is only within recent years that the steam turbine has come into its own. In his day de Branca stood alone, however, and research on the steam engine reverted to the line of progress indicated by della Porta.

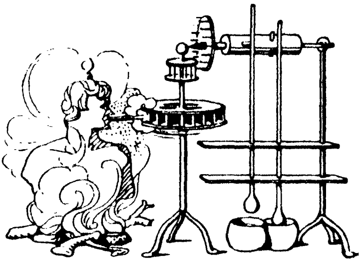


FIG. 18.—Branca's Forerunner of the Steam Turbine.

The need for such research was visibly growing. The flooding of mines was offering continual trouble. Mech-

anisms were required for the mechanical crushing and washing of ore. The necessity for mechanical assistance to move vessels against wind and tide was recognized. Industrial activity generally was, in fact, making its appeal to applied science to come to its aid at a time when science itself was receiving a gratifying stimulus from Galileo, Gilbert, Francis Bacon, and Descartes. Under such circumstances progress was inevitable.

So we come to the picturesque figure of Edward Somerset, Marquis of Worcester.

IV. EDWARD SOMERSET, SECOND MARQUIS OF WORCESTER

The Marquis of Worcester was a man of many accomplishments. In addition to a bent for scientific investigation, he was also a man of affairs. He had a somewhat chequered career. Becoming involved in the Civil War between Charles I and the Parliament, he took up the cause of his King with a vigour which, unfortunately for himself, lost him his fortune and brought him to imprisonment in Ireland. He succeeded, however, in escaping to France, and there joined the Court of the exiled Charles. Returning to England in the rôle of secret agent to the Royal Family, he was detected and thrown into the Tower of London. Here he had the time and leisure to exercise his bent for scientific reflection. The story is told of him, as it was told afterwards of George Stephenson, that whilst in the Tower his attention was attracted to the continual lifting of the lid of a saucepan in which his dinner was cooking. His reflections led him along the path of invention with which his name has since become associated.

Let us consider his claims in his own words:

> 'I have invented', wrote he, 'an admirable and forcible way to drive up water by fire . . . For I have taken a piece of whole cannon, whereof the end was burst, and filled it three-quarters full of water, stopping and screwing up the broken end, and also the touch-hole, and making a constant fire under it; within twenty-four hours it burst, and made a great crack.

So that, having a way to make my vessels so that they are strengthened by the force within them, and the one to fill up after the other, I have seen the water run like a constant fountain stream forty feet high. One vessel of water rarefied by fire driveth up forty of cold water, and a man that tends the work has but to turn two cocks; that one vessel of water being consumed, another begins to force and refill with cold water, and so successively; the fire being tended and being kept constant, which the selfsame person may likewise abundantly perform in the interim between the necessity of turning the said cocks.'

Two descriptions of Worcester's engine exist. Of one, printed on a single leaf and undated, the only known copy is in the possession of the British Museum. It was probably written for the purpose of interesting subscribers to a water company, and we know that his engine was actually used for the raising of water at Vauxhall. In this Worcester speaks of his design as a 'water commanding engine, boundless for height or quantity, requiring no external or even additional help or force to be set or continued in motion, but what intrinsically is afforded from its own operation, nor yet the twentieth part thereof'. The concluding words of this description are interesting. 'Whosoever is master of weight is master of force; whosoever is master of water is master of both, and consequently to him all forcible actions and achievements are easier.'

The second description of the engine is included in the pages of a work published by the Marquis of Worcester in 1663 under the title *A Century of the Names and Scantlings of Invention by me already practised*—a vaguely worded account of a variety of contrivances. Yet in neither of these two accounts is there sufficient material for the definite reconstruction of his engine. No drawing was left by the writer. Attempts at reconstruction, so far as dimensions are concerned, have been based largely on the remains of cells and grooves in the walls of the citadel of Raglan Castle, where Worcester almost certainly erected his first engine about the year 1628. The second engine intended for Vauxhall appears to have been erected nearly twenty years later, in 1647. Yet later, in 1663, the year of the publication of his *Century*

of Inventions, the Marquis of Worcester secured his patent by Act of Parliament. By this Act it was decreed that a tenth of the profits should go to the King (Charles II), although actually the King remitted this share by way of cancellation of a debt of £40,000 acknowledged to be due to Worcester from him.

Lord Worcester died in poor circumstances in 1667. He was buried in the cemetery of the Beaufort family in Raglan Church. He left a request that a model of his engine should be buried with him, but it is not known whether this was carried out. The probability is that it was not.

V. THE SECOND HALF OF THE SEVENTEENTH CENTURY

Attention to the whole problem of steam and its utilization in practice was now becoming more vigorous. Scholars like Bishop Wilkins (the author of the famous *Mathematical Magic*) were making more and more insistent references to the possibilities, whilst various men of more or less practical bent were patenting schemes, chiefly of a futile character. The practical sympathies of King Charles II were important and helpful. He created the post of Master Mechanic to the Royal Household, and as a matter of fact the first occupant of this post, Sir Samuel Morland, contributed very materially to the development of the whole subject.

Before considering this, however, we have to notice briefly the work of Jean Hautefeuille of Orleans. He was the son of a baker whom good fortune brought out of the lowly sphere of his own home at a very early age. Although a theorist and man of ideas rather than an experimenter, his tendencies were largely mechanical. In 1678 he proposed the substitution of alcohol for steam as the working fluid. Alcohol is volatile, and is therefore easily evaporated and easily recondensed. Hautefeuille's suggestion was that the alcohol should be alternately evaporated and condensed, so that we have here the

first example of surface-condensation and the use of the same fluid over and over again. His second suggestion was important. It was no less than the introduction of a piston working in a cylinder. His third suggestion was linked up with the second, in that he proposed something in the nature of an internal combustion engine by using gunpowder to raise the piston upwards.

This idea appealed very strongly to Christian Huyghens (1629–1695), the brilliant Dutch scientist of this era, and in 1680 he designed an engine based entirely on Hautefeuille's suggestions. His scheme, which brings us for the first time to anything really approaching the principle of the engine of to-day, is shown diagrammatically in Fig. 19. Working in a cylinder A is a piston B attached by a rope passing over a pulley C to a counterweight W. D and D′ are two outlet pipes fitted with check valves, and H is the gunpowder chamber at the base of the cylinder. The action is very simple. On the explosion of the charge in H the piston B is forced up and the weight W moves down, the air above B being expelled through D and D′. The products of explosion below the piston now cool, and accordingly contract. This causes a reduction in pressure below the piston, and the superior atmospheric pressure above forces the piston down again. As a result the weight W moves up, thus performing useful work.

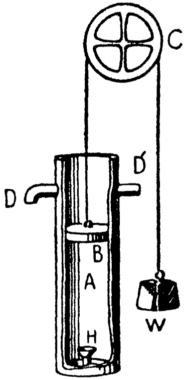


FIG. 19. — Huyghens' Forerunner of the Internal Combustion Engine.

Meanwhile, the general properties of steam apart from the practical question of a steam engine were beginning to be studied. We have already referred to Sir Samuel Morland as having been appointed Master Mechanic to the King. Always interested in mechanical sciences,

this investigator began a quantitative study of the properties of steam. His results were surprisingly correct considering the limited scope for exact experiment in his days. The property of latent heat was not yet known, and Morland's work was in effect a study of the relationship between pressure and volume. He embodied his results in a work which he dedicated to King Louis XIV (who had commissioned him to construct some pumps in Paris) in 1682, in the course of which he says:

'Water being evaporated by fire, the vapours require a greater space (about two thousand times) than that occupied by the water, and, rather than submit to imprisonment, it will burst a piece of ordnance. But, being controlled according to the laws of Statics, and, by science, reduced to the measure of weight and balance, it bears its burden peaceably (like good horses), and thus may be of great use to mankind, especially for the raising of water.'

VI. SAVERY

Morland's work marks a distinct advance in the study of the whole problem of the steam engine, if only because the mechanical aspect of the problem began, for perhaps the first time, to receive recognition. Nevertheless, until the engine could be devised which was capable of doing mechanical work other than the mere pumping of water, we must still regard the development of the steam engine as being in its preliminary stages. Before we pass beyond this phase of its history, one more pioneer, Thomas Savery, claims our attention. Savery was born at Shilston about 1650. He came from a Devonshire family, and was trained as a military engineer. He was essentially an experimentalist. The problem of mechanical propulsion interested him from the outset of his career, and he invented a method for propelling vessels in calm weather by an arrangement of paddle wheels driven by a capstan. He will always be remembered, however, for his work on the steam engine. The great need for the clearing of Cornish

mines and pits from water had attracted his attention, and Savery was not long in devising what was probably the first commercially successful water-raising engine. Its principle is illustrated in Fig. 20. Steam was generated in the boiler B and was then passed into a large closed vessel A, in the lower part of which was water, and in the upper part air. The effect of the generation of the steam in B was clearly to drive the

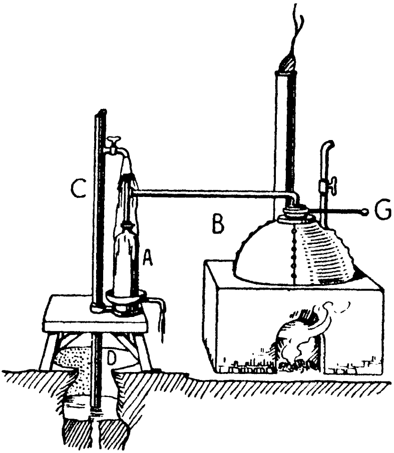


FIG. 20.—Savery's Design for Water-pumping Engine.

air from A up the pipe C. The vessel A was now cooled by pouring cold water on it, thus condensing the steam in A which had replaced the air. The great reduction in pressure thus resulting caused water to be drawn up from the well (or mine) below through the valve and pump barrel at the head of the water pipe D. A further valve higher up was so placed as to prevent the air from the pipe C from returning to A. Steam was then once again admitted to A from B, this time forcing the water in A, upon which it was pressing, up the pipe C, the valve

at the top of D being closed. This gave a definite head of water in the pipe C, and by repeating this process the level of the water in C rose continually—ultimately to a height of 42 feet—until it reached the surface.

Savery patented the design in 1698, and exhibited a model of it to the Royal Society in the following year. The success of this model encouraged him to proceed to the construction of a full-scale engine, which he began extensively to advertise in a pamphlet entitled *The Miner's Friend, or A Description of an Engine to Raise Water by Fire described, and the Manner of Fixing it in Mines, with an Account of the Several Uses it is Applicable to, and an Answer to the Objections against It.* This pamphlet, distributed in 1702, came at an opportune moment. Without some such aid as that of the 'Fire Engine', as the steam-engine was then called, the cost of clearing the mines of water was virtually absorbing all the profit the mine-owners were deriving from the sale of their ore. This is not surprising if we remember that the usual method employed was that of the horse-gin and buckets, and that in one mine no fewer than 500 horses had to be employed for this purpose.

Fig. 21 illustrates the full-scale pumping engine developed by Savery in 1702. Steam is admitted from the boiler L to one of the two oval vessels P, displacing the water which is driven up the pipe S through the check valve *r*. When P is emptied the supply of steam is stopped, the valve *r* is closed, and the valve M opened. A cold-water jet from the cistern X above it is now played upon P. A partial vacuum is produced, and water is therefore sucked up from the mine or well through the pipe T. The whole process is then repeated, and so on. The system of vessel and valves P, M and *r* is duplicated in order to maintain a continuous action, so that when steam is being delivered into one of the vessels P, the condensing jet from X is playing upon the other, and vice versa. It should be noticed that Savery had two boilers and furnaces, here again constituting a definite improvement upon the earlier design by the

Marquis of Worcester. The supplementary boiler Z and furnace B was filled while cold, and a fire was lighted under it, and it enabled Savery to supply the working boiler with water without interrupting the working of the engine as a whole. The other distinct advance in design was in the automatic system of surface condensa-

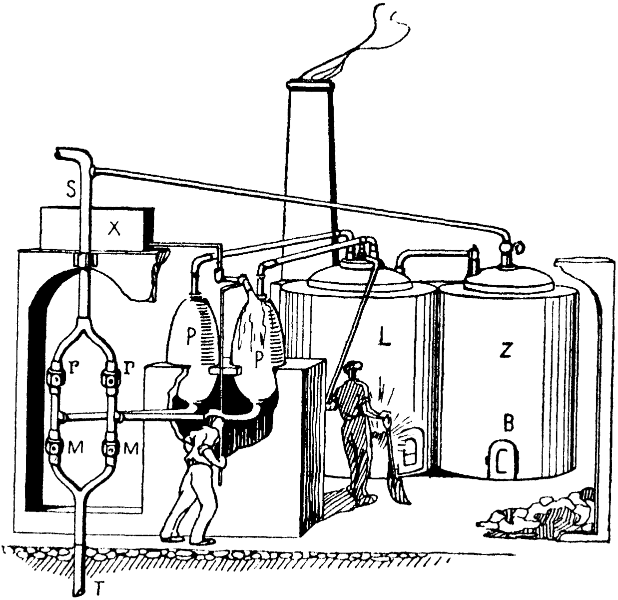


FIG. 21.—Savery's Full-scale Pumping Engine, 1702.

tion. Savery's engine was the first definitely to find employment in the mines. It was not altogether a success, because in working it at a great depth he was compelled to use greater pressures than the boilers could stand. Nor did he fit safety valves to his boilers, although this was an improvement to come shortly after.

As was the case with so many other investigators at this time, Savery was really beaten by the crude workmanship that was inevitable owing to the poor tools that were then available. He complained that the high pressure of the steam melted the solder at the joints, but apart from this the waste of fuel was enormous, the consumption of coal being some twenty times as great as that needed for the same amount of work to-day. In addition to this, there was the great wastage due to the condensation of steam on the surface of the water and on the sides of the displacement chamber at each stroke. It is interesting to note in passing that Thomas Savery was probably the first inventor to use the term 'horse-power' in describing the amount of work of which his engine was capable. Savery's engine, as a matter of fact, was not only used in a number of mines, but also on large estates and for supplying towns with water. He even proposed its use for driving mills, but there is no evidence to show that this was actually done. On the whole, however, its use was very limited indeed, but in so far as it was the first type of engine to find commercial application, we must accord to Thomas Savery a place of honour in the history of engineering.

CHAPTER VI

DENYS PAPIN AND THOMAS NEWCOMEN—THE ADVENT OF STEAM POWER

I. DENYS PAPIN

DENYS PAPIN, the next inventor to claim our attention, was a Frenchman by birth. He was educated in the Jesuit School at Blois, and later studied medicine both at Paris and at Orleans. He settled in Paris in 1672 with the intention of pursuing a medical career. Fortunately he came under the influence of the great Dutch philosopher, Huyghens, and the two carried out a number of investigations in mechanics. As a result Papin soon acquired a considerable reputation. He came to England in the year 1675, and here he met the Honourable Robert Boyle, who was at this time carrying out his well-known experiments on the mechanical properties of the atmosphere. Papin invented his famous digester in 1680 whilst he was in England. In 1687 he accepted a professorial appointment in Germany. It was during his sojourn there that he devised the plans for the steam engine which constitute his chief claim to fame. Papin's idea, developed in 1690, was to fit a cylinder with a piston which was driven upwards by the force of expanding steam and downwards by the atmospheric pressure above it after a vacuum had been created through the subsequent condensation of the steam. Papin derived his idea from Huyghens' original conception of causing a piston to move by the explosive force of gunpowder. In effect, Papin substituted the

steam for the gunpowder in Huyghens' original design. He caused water to boil under the piston, and as a result of the formation of the steam the piston ascended. When it reached the top of its stroke, he cut off the supply of heat and caused the piston to be held in its place by hooking the piston rod to a suitably placed rope passing over a fixed pulley.

In the absence of the heat from the boiling water, the cylinder then cooled, causing the steam to condense, and thus creating a vacuum, so that on releasing the piston rod from the hook the piston was forced down. If, instead of connecting it with a fixed rope, the piston was on its return stroke attached to a beam connected with a pump in the mine, and then released, its downward motion would cause the beam to raise the water in the pump pipe through a short distance. Clearly this was a very slow and tedious operation. Nevertheless, this was the first design in history in which the idea was used of a piston moving in a cylinder in one direction by the expansive force of steam, and in the other by atmospheric pressure after the creation of a vacuum. We have here, in fact, the true seed of the modern steam engine.

In Papin's original model the cylinder was 2½ inches in diameter and it raised a load of 60 lb. once a minute. It was calculated by Papin that with a machine whose cylinder was 2 feet in diameter and whose stroke was 4 feet he could develop about one horse-power.

Papin was of course faced with the difficulties of crude workmanship so common to all engineers of those times. He could not hope for truly-turned cylinders of any appreciable size. Another feature which rendered his design of little use was the fact that he proposed to use a single vessel for the dual rôle of cylinder and boiler. There is, however, one further design by Papin to which we must refer. In 1705 he received from the great German philosopher Leibnitz, who had just returned from a visit to England, some details of Savery's engine. Papin at once directed his mechanical genius towards improving it. As a result he devised an engine, the

details of which are shown diagrammatically in Fig. 22. A displacement chamber A, shaped as shown, acted as a cylinder, and contained a floating diaphragm or piston P, whose rôle was to separate the water below it from the steam above it. The water was forced by the power of the expansive steam above into a closed air vessel B, and from B it was delivered through a pipe in a continuous stream against the veins of a water-wheel. The steam was generated in a boiler to the right, and after it

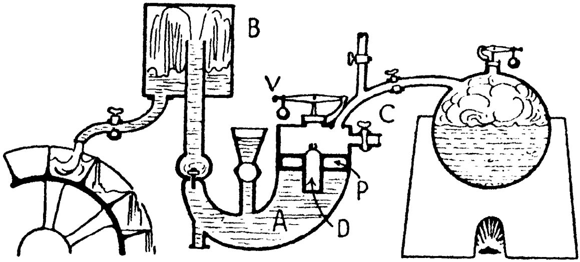


Fig. 22.—Denys Papin's Engine—Note Steam Lever Safety-valve.

had done its work it was not condensed, but was allowed to escape from the displacement chamber by the stopcock C. A lever safety valve V was fitted to the cylinder, and the piston or float was supplied at its centre with a hot mass of metal D, the object of which was to keep the steam dry. It will be seen that, as in his earlier design, Papin again used the same chamber both as a steam cylinder and pump cylinder. Here clearly Papin went back a step from his first invention. His design met with little success commercially, and he died in 1810 a somewhat disheartened man.

II. THOMAS NEWCOMEN

Fortunately for the reputation of our own country, almost the whole of the subsequent and more important story of the steam engine deals with Englishmen and

England. The various ingredients contributing to the make-up of a successful design were now known. Boyle in England and Mariotte in France had accomplished their great researches on the properties of the atmosphere, and the utilization of steam through its condensation for the purpose of creating a vacuum was understood. Again in the workshop steam boilers and steam cylinders were being produced, and the valuable device of the steam safety-valve was available. All that was wanted was the ingenuity of some designer who could blend these factors together with the maximum of efficiency and a minimum of complication, and it is fortunate that in Thomas Newcomen and in James Watt such men were at hand.

Thomas Newcomen was born of humble parentage at Dartmouth in 1663. He was apprenticed to an ironmonger and blacksmith in his native town, but little is known of his early career. It is clear, however, that he had been employed by Captain Savery, and that as a result of this employment he became greatly interested in the whole problem of the steam engine. His association with Savery, who was then living at Modbury, some fifteen miles from Dartmouth, probably arose from the latter's great need of skilled workmen. Newcomen had evidently established a reputation for skill in his trade, and was accordingly taken into Savery's employ. It will be remembered that Savery's original patent was taken out in the year 1698, but there are evidences that Newcomen had himself made alterations in the design in the year 1705, in collaboration with one John Calley, a glazier of Dartmouth, of whom very little is known.

In this design steam was generated in a separate boiler and so conveyed into a vertical cylinder beneath a piston that was capable of moving up and down throughout the whole length of the cylinder. Attached to this piston was a rod which in its turn was attached to the end of a horizontal lever pivoted at its centre, and connected at the other end with the heavy piston rod of a mine pump. This pump rod acted as a counterweight. When the

piston in the cylinder was raised by the counterweight effect of the pump rod, steam was admitted from the boiler into the cylinder. Cold water was now applied to the sides of the cylinder, thus condensing the steam and producing a vacuum. As a result the air pressure above now forced the piston down and so raised the pump rod. By continuously repeating this process the pump was made to operate. The essential difference between this design and Savery's was that Newcomen worked entirely by the effect of atmospheric pressure, the function of the steam being only to produce the vacuum through condensation, whereas Savery also utilized the expansive force of the steam. Newcomen's design was very clumsy, but it found commercial application in a number of mines.

By the year 1712 Newcomen had succeeded in effecting some important improvements in his engine. The most important was in the method employed for producing the condensation of steam. Instead of doing this by the application of cold water to the outside of the cylinder, a jet of water J was sprayed directly into the cylinder itself (Fig. 23). The idea for this was derived accidentally from the chance observation of a defect. In order to keep the cylinder as free from air as possible, the sides of the piston had been carefully packed with cloth or leather, and in addition a layer of water had been maintained constantly on the upper side of the piston. On one occasion Newcomen was surprised to notice his engine working with unusual speed for a succession of strokes. He was naturally pleased, but was curious as to the cause. He traced this to a hole in the piston through which the cold water was leaking into the cylinder below, acting as a jet, and thus producing a rapid vacuum by the condensation of the steam with which it came into contact. Newcomen at once embodied this idea in the permanent design and with immediate effect. Yet another chance experience led to the second improvement. Normally the working of a Newcomen engine required three workmen—one to

attend to the fire, one to admit the steam into the cylinder, and a third to admit the jet of cold water to condense the steam. The following extract from a contemporary account brings this out very well:

'I have heard it said that when the engine was stopped and again set to work, the words were passed, "Snift, Benjy", "Blow the fire, Pomery", "Work away, Joe". The last let in the condensing water. Lifting the condensing clack was called snifting, because on opening the valve the air rushing through it made a noise like a man snifting. The fire was increased through artificial means by another hand, and all being ready the machine was set in motion by a third.'

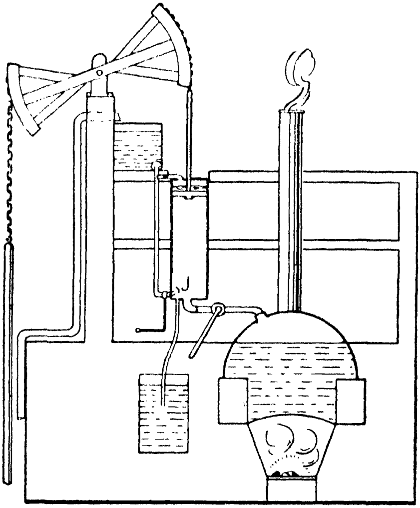


FIG. 23.—Newcomen's Steam Engine.

Later only two were found necessary: a man to attend to the fire, and a boy to manipulate alternately the steam-admission cock and the cold-water jet.

The story goes that one such lad, named Humphrey Potter, finding his work very monotonous, devised an arrangement of strings and catches whereby the two

cocks were worked automatically from the alternate up and down movement of the engine beam over his head. This device, though crude, was not only efficient but distinctly improved the efficiency of the engine itself, and the number of strokes was increased from eight to fifteen or sixteen. Later, in 1718, Henry Beighton simplified Potter's device by suspending from the beam a rod known as the plug-tree, which worked the valves by means of tappets.

Thurston gives an instructive example [1] of the capabilities of a Newcomen as compared with a Savery engine of similar size. In a Newcomen machine used for the drainage of mines the diameter of the pump was 8 inches and the lift was 162 feet. The diameter of the steam piston employed was 2 feet. The amount of water to be raised was naturally the weight of a column 162 feet high and 8 inches in diameter. This gave 3,535 lb. The net working pressure was $10\frac{3}{4}$ lb. per square inch, and since the area of the piston worked out to 452 square inches, this gave a total pressure on the piston of $452 \times 10\frac{3}{4} = 4{,}859$ lb. Hence the excess of pressure on the steam side over that on the water side was $4{,}859 - 3{,}535 = 1{,}324$ lb. Now approximately one half of this excess was taken up by the pump rods and the counter-weight on the beam, so that 662 lb. was the force actually producing a movement of the piston. The engine worked at 15 strokes per minute, giving a speed for the piston itself of 75 feet per minute. Hence in modern units the rate of working was 75×662 ft. lb. per minute. This meant a horse-power of approximately 8. As against this a Savery engine would have raised the water about 26 feet in the suction pipe, and only under a steam pressure of 60 lb. per square inch would it have succeeded in forcing the water the remaining 136 feet, in order to give the total 162 feet lift. At this high temperature and pressure, however, the waste of steam by condensation would have been enormous.

[1] Thurston: *A History of the Steam Engine*, 1895.

Newcomen's engines did in fact come into general use in all mining districts and were even occasionally employed for the drainage of wet country. Afterwards they were largely built and erected by J. M. Smeaton, who was one of the most distinguished engineers of his day. Without in any way altering the principle he developed greater efficiency by careful attention to detail, so that by the end of the eighteenth century the Newcomen engine was an established feature in commercial practice.

CHAPTER VII

JAMES WATT

I. EARLY CAREER

WITH the advent of the steam engine as a factor in commercial production, a definite stage in its evolution was reached. Further developments could naturally only follow the path of increased efficiency. The next inventor, in fact, could merely study the existing design in order to eliminate the various sources of waste and inefficiency, and so build up a new and improved design. We cannot attach too much importance to this phase of the development of the steam engine. Its effects upon commercial life and the world of engineering were enormous, and because the problems in question were indeed difficult, great honour attaches to the name and memory of James Watt, the man who did more to improve and perfect the steam engine than any other person.

James Watt was born at Greenock in Scotland on January 19, 1736. He was the son of a mathematical instrument maker and the grandson of a mathematician. His father, a man greatly respected in the community in which he lived, saw with some concern that James was a very delicate child. Instead, therefore, of subjecting the child to educational restraints, he allowed him considerable liberty to choose his own occupations and amusements. Little Watt spent much of his time in his father's workshop, and developed a liking for mathematical work. The father noted with pleasure

the many ingenious pieces of mechanism that the boy was making, and he did all he could to encourage him. James happily proved to be a prolific reader of books. Consequently when, at the age of eighteen, he was sent to Glasgow to reside with his mother's relatives to learn the trade of a mathematical instrument maker, he was not only equipped with a ready ability to handle tools, but also with a considerable amount of mathematical knowledge. Watt did not stay long with his first master. In June, 1755, he left Glasgow and found employment in London for a short time. Within a year, however, ill-health compelled his return to Glasgow, where he definitely opened a business as a mathematical instrument maker to the university.

There were at this time two personalities at the university who were strongly to influence James Watt in his career. One of these was Dr. Robinson. He was then a student, but was afterwards to become a distinguished master of science. The other was the famous Dr. Joseph Black, one of the greatest philosophers of his day. Dr. Black was, through his researches in specific and latent heat, the founder of the study of heat as a quantitative science. These investigations were in fact actually proceeding about this time, and it was in connexion with them that Watt found himself drawn to the study of the steam engine.

II. FIRST IDEAS

There was in the possession of the college a model of the Newcomen engine in a state of disrepair. It was at the suggestion of John Robinson that Watt began to interest himself in it, and this in its turn led to the suggestion that Watt should repair the Newcomen model. He was not long in putting it in good working order, and he then began to experiment upon it. He soon found that the boiler of this model engine was much too small for the purpose required, and Watt not only made a new boiler for it but arranged it in such a

way as to enable him to measure both the quantity of water evaporated and the amount of steam used at each stroke of the engine.

We see in the approach to these problems a frame of mind very different from those of past workers. We may say, in fact, that Watt was considering his problem rather from the scientific standpoint than from the engineering standpoint. Undoubtedly, however, this proved to be the right road to engineering efficiency. In fact the days of empirical design were over. Watt soon discovered how very small a quantity of steam was necessary in order to heat a larger quantity of water. He proceeded to determine as best he could the relative weights of steam and water in the cylinder when condensation took place at the down-stroke of the engine, and in effect he was really proving by these means the existence of that 'latent heat' which Dr. Black had already established by other methods. Watt saw that at the temperature of boiling water steam could, in its condensation, supply considerable heat to many times its own weight of water. In other words, weight for weight, the steam was a much greater source for the supply of heat than was hot water. The inference to Watt was clear and important. It would never do to waste steam where such waste could be avoided. In the Newcomen engine there was considerable waste. Where then was the source of this waste? He first thought of the boiler, and in order to prevent losses of heat by conduction and radiation he provided his boilers with wooden covers and at the same time used a larger number of flues in order to ensure that he was utilizing all the heat from the hot furnace gases. He extended this scheme to the covering of his steam pipes with non-conducting material. Nevertheless, in spite of these improvements, Watt still found the Newcomen engine to be wasteful of enormous quantities of heat. The main source of loss was, in fact, not so much in the boiler as in the cylinder itself. Watt summarized the sources of loss as being (1) the dissipation of heat by the

cylinder itself, (2) the loss due to the necessity of cooling the cylinder by means of the water jet used at every stroke in order to produce the vacuum, and (3) the loss of power due to the pressure of vapour under the piston because all the steam was not condensed. He accordingly carried out a series of very accurate experiments on these points, and in particular he investigated the temperatures and pressures of steam over as wide a range as possible, and he represented these results graphically. From them he found quite conclusively that, with the amount of water injected into the cylinder at each stroke, the temperature was reduced by amounts varying from 140° F. to 175° F., thus setting up serious back pressures. He also proved that three-fourths of the amount of steam used at each stroke was wasted.

Clearly Watt realized that in order to avoid all this waste he must find some means of keeping the cylinder always as hot as the steam that entered it, and the means for accomplishing this occurred to him in the manner best described in his own words:

> 'I had gone to take a walk on a fine Sabbath afternoon. I had entered the Green by the gate at the foot of Charlotte Street and had passed the old washing house. I was thinking upon the engine at the time, and had gone so far as the Herds House when the idea came into my mind that, as steam was an elastic body, it would rush into a vacuum, and, if communication were made between the cylinder and an exhaustive vessel, it would rush into it, and might be there condensed without cooling the cylinder. I then saw that I must get rid of the condensed steam and injection water if I used a jet, as in Newcomen's engine. Two ways of doing this occurred to me: first, the water might be run off by a descending pipe, if an offlet could be got to the depth of 35 or 36 feet, and any air might be extracted by a small pump. The second was to make the pump large enough to extract both water and air.'

Thus was Watt led to his great invention of the separate condenser. The next day he proceeded to test his ideas by means of a model experiment. Briefly he was adding to the engine a new constituent—an empty vessel, separate from the cylinder, into which the steam should be allowed to escape from it and be condensed

by the application of cold water either outside or as a jet. Further, in order to preserve the vacuum in the condenser, he proposed to add an air pump whose function it was to pump from the condenser both the condensed steam and water and also the air which would otherwise accumulate from leakage or from being in contact with the steam or the injection water. Thirdly, as the cylinder was no longer to be used in the rôle of condenser, there was no longer any need to chill it, and so Watt proposed to keep it hot by surrounding it with non-conducting material, suggesting for this purpose a steam jacket between the cylinder and the outside casing. Lastly, and again with the same purpose in view, Watt proposed covering in the top of the cylinder, and he arranged that the piston rod should pass out through a steam-tight stuffing-box.

Watt's experimental apparatus is shown in Fig. 24. A is the cylinder, B the surface condenser, and C the air pump. The cylinder was filled with steam above the piston and a partial vacuum was formed in the surface condenser B. When the stopcock D was opened, the steam rushed over from the cylinder into the condenser and was at once condensed. As an immediate consequence the piston rose and lifted a weight.

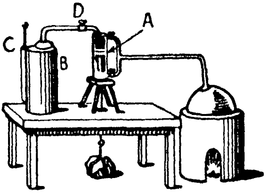


FIG. 24.—Watt's Experimental Model for Improvement of the Steam Engine.

III. THE PATENT OF 1769

Watt now began to apply the lessons of this model to a large-scale design, and gradually there emerged an engine which Watt patented in 1769. The specification in which Watt described his patent marks such a great advance in the scientific aspect of the whole problem that we quote the more important portions of it in full:

'My method of lessening the consumption of steam, and consequently the fuel, in fire engines, consists in the following principles:

'*First*, that the vessel in which the powers of steam are to be employed to work the engine—which is called the cylinder in common fire-engines, and which I call the "steam vessel"—must, during the whole time that the engine is at work, be kept as hot as the steam that enters it; first, by enclosing it in a case of wood, or any other materials that transmit heat slowly; secondly, by surrounding it with steam or other heated bodies; and thirdly, by suffering neither water nor any other substance colder than the steam to enter or touch it during that time.

'*Secondly*, in engines that are to be worked, wholly or partially, by condensation of steam, the steam is to be condensed in vessels distinct from the steam vessel or cylinder, though occasionally communicating with them. These vessels I call "condensers"; and while the engines are working these condensers ought at least to be kept as cold as the air in the neighbourhood of the engines, by the application of water or other cold bodies.

'*Thirdly*, whatever air or other elastic vapour is not condensed by the cold of the condenser, and may impede the working of the engine, is to be drawn out of the steam vessels or condensers by means of pumps, wrought by the engines themselves, or otherwise.

'*Fourthly*, I intend in many cases to employ the expansive force of steam to press on the pistons, or whatever may be used instead of them, in the same manner as the pressure of the atmosphere is now employed in common fire-engines [he is here referring to the Newcomen engine]. In cases where cold water cannot be had in plenty, the engines may be wrought by this force of steam only, by discharging the steam into the open air after it has done its office.

'*Fifthly* [there follows a reference to a rotary engine, which does not concern us here].

'*Sixthly*, I intend in some cases to apply a degree of cold not capable of reducing the steam to water, but of contracting it considerably, so that the engine shall be worked by the alternative expansion and contraction of the steam.

'*Lastly*, instead of using water to render the pistons or other parts of the engine steam-tight, I employ oils, wax, resinous bodies, fats of animals, etc.'

In order to produce an engine model on these lines, Watt hired a room in an old pottery, and here, through the good offices of Dr. Black, he became acquainted with Dr. Roebuck, who had just started the famous Carron Iron Works, of which we shall have more to say

in the next chapter. The expenses to which Watt was put as a result of his experiments considerably impoverished him, but now Dr. Roebuck agreed to finance him, and the two went into partnership.

IV. FURTHER DEVELOPMENTS

The first engine made by Watt in 1769 was not a great success. The condenser was of the surface type and was not sufficiently water- and steam-tight, and the piston leaked very seriously. Watt became very despondent, and in his anxiety to relieve Dr. Roebuck of the financial losses that threatened he looked round for other help. This luckily came to hand in the person of Matthew Boulton, the son of a Birmingham engineer, whom Watt had met during a journey to London for the purpose of securing his patent. Thus was set up the famous partnership of Boulton and Watt that so greatly enriched the profession of engineering. Nevertheless, it was not until 1774 that the first really successful single-acting engine was erected. This is illustrated in Fig. 25. It will be seen that the top of the cylinder is closed, but that the steam has access to the upper side of the piston through the admission pipe on the left. This ensured keeping the piston and cylinder warm, but nevertheless the steam on this upper side merely served the same purpose as did the air in the former Newcomen engine. The lower end of the cylinder communicated with the condenser C. Three valves figure in the design: the steam valve *a*, the equilibrium valve *b*, and the exhaust valve *c*. The action is briefly as follows: At the beginning of the down stroke the exhaust valve *c* is opened to produce a vacuum below the piston, and the steam valve *a* is opened to admit steam above it. At the end of the down stroke both these valves are shut, and the equilibrium valve *b* is opened. As a result the pressure is the same on both sides of the piston, which is thus compelled to be pulled up by the heavy pump rod *p*

acting as a counterpoise. *b* is now closed and *a* and *c* opened as before, and so the process is repeated. C is the condenser, and the air pump discharges the water of condensation into the hot well *h* whence the supply of the feed pump *f* is drawn.

The success of this engine at once brought orders to the firm of Boulton and Watt. The period of the patent was suitably extended, and the removal of financial anxieties which resulted enabled Watt to

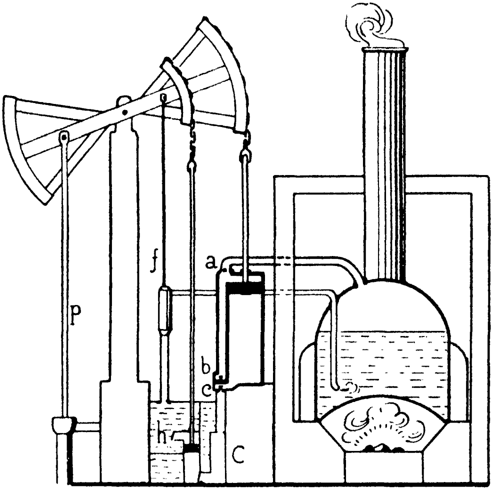


FIG. 25.—Watt's First Successful Single-acting Steam Engine, 1774.

persevere further in his studies and experiments. As a consequence, in 1781 he was able to outline in a further patent a number of important improvements. These included the double-acting steam engine, in which the steam was admitted to each side of the piston alternately, the opposite side being in communication with the condenser. For this purpose Watt devised a steam chest and slide valve, thus bringing the principle of the engine

practically to its present-day position. This improvement really centred round the problem of properly utilizing the expansive force of steam in approximate accordance with Boyle's law. At first Watt suggested cutting off the steam from admission to the cylinder when the piston had completed half its stroke. This meant that the piston would be driven forward for the remaining half by the expansive force of the steam above it. He soon realized, however, that the engine could work just as efficiently and much more economically by cutting off the steam at one quarter of the stroke.

Watt's next step was to add a fly wheel to the crankshaft, and shortly after he was able to pass on to the design of a compound engine in which *two* cylinders were used. He had already invented the scheme for the linking up, by means of a crank, of the reciprocating motion of the piston with the rotary motion of the crankshaft, and consequently the way was now open for the harnessing of the steam engine to the factory as well as to the mine.

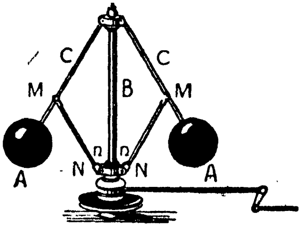


Fig. 26.—The Centrifugal Governor.

Yet one further device of Watt must be mentioned, namely, his invention of the centrifugal governor. This was in effect a conical pendulum, the rotation of which controlled the speed at which the engine could work. Two heavy iron or brass balls (Fig. 26) were suspended from pins from the head of a vertical spindle. The distance of these balls from the spindle was controlled by jointed rods. These were connected by means of a system of levers with the throttle valve of the steam engine. The object of the device was to ensure the uniform working of the engine. When the engine

tended to race, the increased speed would cause the balls to fly outwards, and so to close the throttle and diminish the admission of the steam into the cylinder. As a result the force on the piston would also diminish, thus reducing the speed of the engine. Conversely, if the engine tended to slow down the balls would move inwards, causing the throttle to open and admit more steam, and thus speeding up the engine.

By 1784 the Watt Double-Acting Steam Engine had

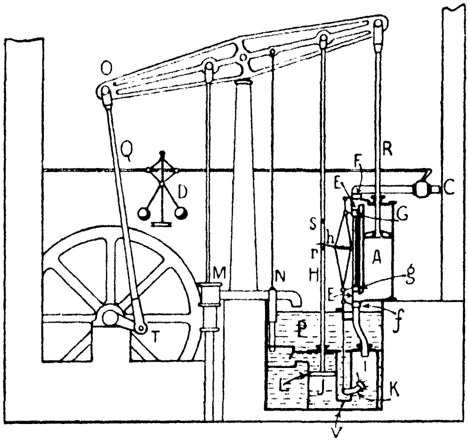


FIG. 27.—Watt's Double-acting Steam Engine, 1784.

taken the form shown in Fig. 27. Steam was passed from the boiler to the cylinder along the steam pipe through the throttle valve C. This valve was in communication with the governor D. On one side of the cylinder were the hollow steam chests EE, each fitted with two valves dividing them into three compartments. The top compartments of both chests communicated with the steam pipe, and the lower compartments with the exhaust pipe leading to the condenser. The linkage system was such that the valves worked in pairs, the

upper inlet valve F and the lower outlet *f* moving together, and similarly the upper exhaust valve G and the lower inlet valve *g*. The piston R fitted accurately into the cylinder by means of a stuffing-box. Hence on opening the valves F and *f*, steam was admitted above the piston and was at the same time withdrawn from below the piston to the condenser. Similarly by opening the valves G and *g* steam was withdrawn from above the piston and admitted below it. All these valves were controlled by a single lever H. The condensing apparatus comprised two cylinders I and J immersed in a cistern of cold water. The pipe K was fitted with a rose and conveyed water from the cistern to the cylinder I, the supply being regulated by a cock. As a consequence the steam passing into I from the cylinder A was condensed. The cylinder J formed part of the air pump, and was fitted with a well-packed piston L containing a valve similar to the bucket valve of a common pump. This valve opened upwards, drawing off the surplus water as fast as it collected at the bottom of the condenser I through the connecting passage and valve V at the bottom. The hot-water pump N now conveyed this water into the tank that supplied the boiler through the reservoir. M was a cold-water pump which supplied the cistern P containing the air pump and condenser so as to keep it cool. Two pins *r* and *s* were placed on the right of the air pump so as to project outwards and strike the lever H upwards and downwards at the proper times when the piston was nearing the termination of its strokes on the top and bottom of the cylinder respectively. Above this structure was the beam of the engine, and at one end O a cast iron rod Q, known as the connecting rod, was attached, and this was fixed at its other end to the crank T and the crankshaft carrying the flywheel.

The engine worked as follows: When the piston was at the top of its stroke, the whole space below being filled with steam, the upper steam-valve and the lower exhaust-valve were opened by the knocking of the lower

pin *r* of the air pump rod against the lever H. The upper exhaust-valve and the lower steam-valve were closed. As a result steam was admitted above the piston and drawn off below it into the condenser, and was there condensed into water. The pressure of the steam above now forced the piston down, and as it neared the end of its stroke the upper pin *s* on the rod of the air pump reversed the lever H, opening the valves that were previously closed and closing those that were previously opened. This now reversed the motion of the piston, and so on successively. Meanwhile the air pump was drawing off the hot water in the condenser into the upper reservoir, and at the same time the hot-water pump conveyed this water back again to the tank supplying the water.

The consequences of James Watt's double-acting engine were far reaching. Reasonably efficient in construction, commercially successful in practice, it created a new industrial situation. By linking up the crankshaft of the engine with suitable shafting in the workshop, the large-scale use of machinery in industry became possible. The whole outlook of industrial life was changed, and parallel inventions and improvements in the machinery of the textile and other industries were rapidly effected. Thus was brought about what is known as the Industrial Revolution. A new era for industry was at hand.

V. CONCLUSION

James Watt had now completed his life's work. We are not here concerned with a recital of his many interests and activities, our purpose being merely to place on record his contributions to civilization in the development of the steam engine. He retired from active work in the year 1800 at the age of sixty-two, leaving his two sons (one of whom died a few years afterwards) to carry on the business in continued partnership with Matthew Boulton. Watt spent his retirement at Heathfield, Birmingham, quietly and prosperously. He lived very

simply, and in the attic of his house he set up an experimental workshop in which he was able to maintain his interest in engineering science. He died on the 19th August, 1819, in his eighty-third year, vigorous to the last. To his memory there was erected in Westminster Abbey a marble sitting portrait-statue. With its inscription we may fittingly conclude this chapter:

JAMES WATT,
who, directing the forces of an original genius,
early exercised in philosophic research,
to the improvement of

THE STEAM ENGINE,
enlarged the resources of his country,
increased the power of Man,
and rose to an eminent place among the most
illustrious followers of science and the real
benefactors of the world.

CHAPTER VIII

GAS AND OIL POWER

I. INTRODUCTION

WITH the steam engine an accomplished fact, the application of mechanical power made possible enormous advances in engineering practice and achievement. Two lines of development were inevitable, and both were connected with industry in general. First there was the linking up of the new power with the factory and the workshop. This manifested itself chiefly in the invention of specialized machinery, peculiar to the particular needs of the various factory processes, which could be harnessed to the steam engine by the aid of shafting and belt gearing. These replaced the old hand machines, and in so doing contributed one of the main factors to the Industrial Revolution. Secondly, there was the evolution of mechanical transport, that resulted in the locomotive engine and the steamship. These have been of almost incalculable benefit to mankind.

It is unfortunate that the limitations of space do not permit of our enlarging upon this aspect of engineering history, and upon the work of such great engineers as Trevithick, the two Stephensons, John Fitch, Fulton, Stevens, Parsons, and many others, with which it is associated. It should be noticed that these advances all involved a steady increase in the horse-power capacity of the engines so employed. This greatly increased power capacity was, however, only one of two needs.

There was an equally urgent need for the design of an engine that could operate at lesser horse-power, but for some time this was a problem that lacked practical solution. Its importance lay in the fact that many a factory operation, while requiring more than hand power for efficiency and economy, was nevertheless of too light a character for the use of steam power. For such operations the steam engine was not only costly but prohibitive.

There was then a definite need for a light engine, and as steam could not be utilized as the power source, new proposals for the internal combustion of oils and gases came to be considered. In this chapter we propose to discuss the steps leading to the internal combustion engine which resulted from these proposals.

II. EARLY IDEAS

The beginnings of the gas engine carry us back to the proposal by Huyghens in 1680, reference to which has already been made, to use gunpowder in the cylinder chamber. Papin took up the idea in 1690. He did not succeed, but his efforts were not without merit. Briefly, the procedure was to explode a small quantity of gunpowder in a large cylinder, and so to expel the air through check valves. This would create a partial vacuum in the cylinder on cooling, and the pressure of the atmosphere would then drive the piston down towards the bottom of the vessel, and could thus be made to do work.

We have, however, to pass on another century before coming to the first real example of a gas engine. In 1794 Robert Street patented a mechanism which was essentially a piston working in a motor cylinder. A lever connected this piston to a pump, which was therefore worked by the motion of the piston. By means of a fire beneath the base of the cylinder, it was possible to evaporate a few drops of spirits of turpentine introduced at the base. By drawing up the piston a little way air was admitted to mix with the vapour. A

flame was next inserted through a touch-hole, and the mixture was exploded. As a result the piston was pushed up, causing the pump piston to move down. It was thus possible to raise water. Here were the first glimpses of the modern internal combustion engine.

Street was followed in 1799 by Lebon, who in a French patent described a scheme whereby a pump could be worked by an internal combustion engine. Feeding a combustion chamber were two compression pumps, one for air, the other for gas. The explosion forced the products of combustion through valves to the motor cylinder containing the piston whose motion was to actuate the pump. Lebon's ideas were vague, and not very practical.

We now come to 1820, in which year Cecil described an engine the object of which was 'to produce a moving power in machinery on the application of hydrogen gas'. Again the basis was an explosion causing a vacuum, and Cecil claimed that at a speed of 60 revolutions per minute he obtained regularly timed explosions, the full consumption rate being 17·6 cubic feet of hydrogen per hour. His was a very noisy device. Cecil, however, attacked his problem in a scientific spirit, and was the first person to attempt to measure the pressures in the cylinders caused by the explosion. His method was to get a tin cylinder 10 inches long by 2 inches in diameter, of a strength sufficient to withstand the force of an explosive mixture of hydrogen and air. This he filled with the gaseous mixture. The cylinder was closed at one end, but the other end was secured by an accurately fitted cork or bung. This was held tightly in its place by a number of strings arranged symmetrically and radially from the centre of the bung, and secured along the length of the cylinder parallel to the axis. By this means the tension was equally distributed. By creating a pressure on a definite area 3 inches square, a number of strings were broken under the force of the explosion. Similar strings were now tested on a steelyard to see how much weight they would stand. The results

showed a pressure of 500 lb. per 3 square inches, or 167 lb. per square inch, and to this the 15 lb. pressure due to the atmosphere was added, giving a result of approximately 180 lb. per square inch. The result was high, but the method was ingenious.

We now come to the period when the internal combustion engine ceases to be a matter for mere theoretical speculation, and merges into the sphere of practical application. In 1823 there was patented by Samuel Brown an engine which, while following the former principle of explosions to produce a vacuum, yet included certain novel and practicable features. The idea was to set up a partial vacuum by producing a flame in a vessel in order to expel some of the air within it, and then putting the flame out by means of a jet of water. Brown presumably derived his idea from the condensing steam engine, substituting the vacuum flame for the steam. In order to get a uniform output of power, Brown arranged for a number of engines, all connected to the same crankshaft, so that they were set at different stages in the cycle of operations. Even so, of course, the motion was irregular. Nevertheless, Brown's engine found definite application in practice, and in 1832 one was in use at Croydon for the purpose of raising water from the canal, and another was employed on drainage operations in the Fen district. There is also evidence that one of Brown's engines was applied to a carriage which, in May, 1826, successfully climbed Shooter's Hill at a gradient of about 1 in 11; whilst in 1827 it was applied to a boat 36 feet long in two tests. It is recorded that on the first day the boat leaked and the river was rough, so that the trial was unsatisfactory, although the boat made some headway; but the second trial, from Blackfriars Bridge, was a great success, the boat making some 7 knots quite smoothly. Nevertheless the Company formed to apply the Brown engine to vessels was dissolved almost immediately afterwards.

Samuel Brown was a true pioneer. He had definitely shown the practical possibilities of the gas engine, and as

a result of his efforts progress in internal combustion engine design became very rapid. This was clear from the designs of W. L. Wright in 1833 of an engine in which the lessons of previous experience were combined with some of the features of a vertical steam engine. In the Wright engine the explosion of the mixture of air and gas was applied directly to the piston. The impulses were timed for every half-revolution of the crankshaft. The gas and air were supplied through two reservoirs from separate pumps at a pressure somewhat above atmospheric, and entered spherical chambers at the ends of the motor cylinder. The explosion (caused by the introduction of an external flame through a touch-hole) pushed the piston either up or down through its whole stroke. The exhaust-valve next opened, and the products of combustion were ejected ; then followed the next explosion, and so on. Both cylinders and piston were surrounded by a water jacket in order to keep the parts cool during the explosion.

The next step, due to William Barnett in 1838, was of great importance. Barnett's contributions to the development of the internal combustion engine were twofold. He was firstly the inventor of the compression system in general use to-day in gas engines. In each of the three designs he proposed, he arranged for the explosive mixture to be compressed before ignition. In two cases this was done by pumps, the mixture being compressed into receivers separated from the motor cylinder by a short port controlled by a piston valve. This valve was also utilized for opening communication between the cylinder and the air during the discharge by the motor piston of the exhaust gases. In the third scheme the mixture of inflammable gas and air was drawn into the motor cylinder by pumps, and in so doing it displaced the exhaust gases of the previous explosion. The mixture was compressed by the motion of the motor piston, partly by the charging pumps, and partly by the motor cylinder itself. In all three designs, however, the ignition was timed to take place when the

crank was crossing the 'dead centre', so that the piston could receive the full impulse of the whole forward stroke.

The second achievement by Barnett was his design of a new form of ignition arrangement. This is indicated in Fig. 28. Fitting accurately into a shell B is a hollow conical plug A. This is kept rigidly in its place by a gland C. Cut into the shell are two long slits *d* and *e*, and the plug is fitted with a port-hole so devised that as

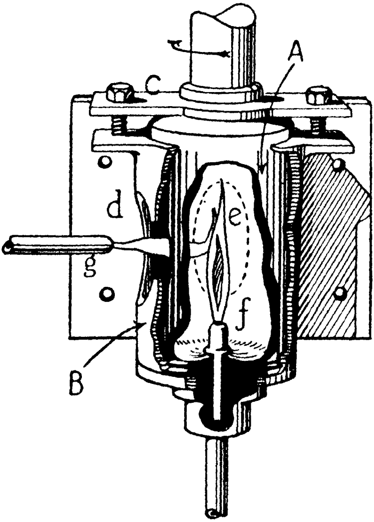


FIG. 28.—The Internal Combustion Engine—Barnett's Scheme for Ignition, 1838.

the plug moves it closes the slit *d* before opening to *e*. A base-cap is screwed into the bottom of the plug, and passing through this is a gas jet *f*. This jet can be lit from an outside fixed flame *g* through the port when this leaves *d* exposed to the air. In this position the inside flame burns quietly and steadily; but if the plug be rotated to close *d* and to open *e*, the outer air is shut out,

whilst the explosive mixture at *e* is ignited. The explosion extinguishes the inside jet of flame, but this is re-lit from outside when the plug once more rotates to its original position. This method of ignition was a distinct advance in gas-engine design, and exists in principle to this day.

III. THE BEGINNING OF THE COMMERCIAL STAGE

Thus far the gas engine was still in its experimental stage. The various problems connected with it had been tackled one by one, and the time was now ripe for collating them into a connected whole. This was done by Lenoir in 1860, and although he embodied little that was new in his design, he deserves credit for being the first to produce a gas engine of real commercial value. Virtually the Lenoir engine (Fig. 29) resembled an ordinary high-pressure steam engine except that valves were arranged to admit both gas and air, and to discharge the products of combustion. The first engine to be so constructed was of 3-horse-power. The piston was impelled forward during the first portion of its stroke by the inertia of the flywheel, while at the same time it drew into the cylinder a suitable mixture of air and gas at normal atmospheric pressure. The valves were then closed, and an electric spark exploded the mixture, thus propelling the piston farther forward to the completion of its stroke. The exhaust arrangements were practically identical with those of the steam engine.

Extravagant claims as to the economical working of this engine were made by its supporters, who asserted that an engine of 1 h.p. would consume about 100 cubic feet of coal gas in twelve hours, which meant about half the fuel cost of a steam engine of corresponding power. As a matter of fact the consumption proved to be three times this amount. Nevertheless the engine was thoroughly sound both from the engineering and from the commercial point of view. It was remarkably

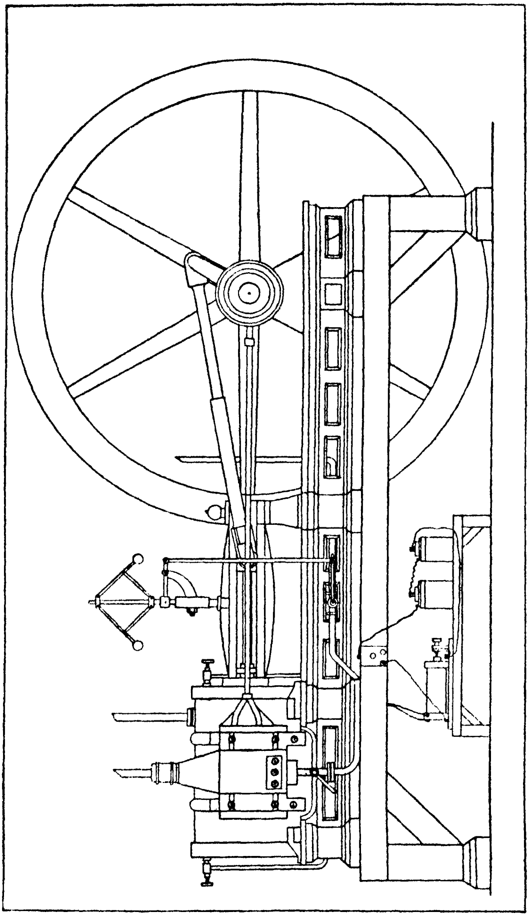


FIG. 29.—The Lenoir Gas Engine, 1860.

smooth in action, and no shock of explosion could be detected. Its cost of construction, too, compared very favourably with that of the steam engine. It is not surprising, therefore, that by 1865 in France there were some 400 such engines at work, and soon a speedy market was found for them in England also. The results fully justified the innovation, and before long such varied operations as pumping, printing, lathe driving, sawing and other processes for which an engine of lower power would suffice were being carried out with the Lenoir engine. Its durability was a notable feature, many such engines continuing in perfect condition after twenty years running. The new form of power soon caused the attention of its investigators to be turned to its possibilities as a medium for mechanical transport, and Lenoir not only designed an experimental road-carriage that succeeded in making a three-hour journey from Paris to Joinville-le-Pont and back, but he also installed a Lenoir engine of 2 h.p. in a boat which plied successfully between Paris and Charenton for over two years, the fuel used being a light volatile hydrocarbon similar to the modern petrol.

At this time only a vague and in many respects incorrect knowledge was current among engineers of the subject of gaseous explosions. Lenoir, for example, believed that the power imparted to the piston was in the nature of a sudden blow, producing a rapid rise in pressure followed by a correspondingly rapid fall, and he therefore assumed that he could obtain better economy of working by inducing a slower explosion by such expedients as 'stratification' and the injection of a steam or water spray. He specifically stated that 'the object of preventing the admixture of air and gas is to avoid explosion'. Such a view on the part of Lenoir was exceedingly inopportune at a time when Bunsen, the famous German chemist, and Hirn, an English investigator, had clearly proved the contrary. Bunsen showed that during the explosion of a mixture of air and gas there was continuous combustion, and Hirn showed that

the heat evolved as a result of such an explosion in a gas engine was in fact only a small fraction of the total heat produced, the remainder being produced during the resulting expansion. Clearly, then, explosion was not to be avoided, but to be induced. Further, the succeeding expansion had to be made as complete as possible.

One can understand, therefore, that the next step in the improvement of the internal combustion engine resulted from a study of the advantages of the preliminary compression of the gas. In 1861 Gustav Schmidt, studying the question of economy in gas-engine practice, offered the suggestion that 'the results would be far more favourable if compression pumps, worked from the engine, compressed the cold air and cold gas to three atmospheres before entrance into the cylinder. By this means', he added, 'a great expansion and transformation of heat is possible.' This clearly was a step in the right direction. It was further developed in 1861, by Million, of France, who, like Schmidt, suggested the use of separate pumps for the compression of the air and gas into a reservoir, in order that the motion of the piston during a portion of its stroke should draw a charge of the mixture into the cylinder under compression, there to be ignited by an electric spark. Million, however, went farther than Schmidt in that he aimed at causing the whole of the piston stroke to be set up by the explosion instead of only a portion of it. To this end he suggested the provision of a space at the end of the cylinder into which the gases could be compressed. His own words express this very clearly:

'Instead of introducing the cold gases into the cylinders during a portion of the stroke and igniting them afterwards, when the induction ceases . . . another arrangement might be adopted. The motive cylinder might be made longer than necessary in order that the piston should always leave a greater or less space between it and the end of the cylinder, according to the pleasure of the constructor, such as one-fourth or one-third, more or less, of the volume generated by the motive piston. This space is called by the inventor a cartridge. On opening the slide valve the gases could be allowed to enter suddenly from the pressure

reservoir into this cartridge towards the dead point, and this induction having ceased an electric spark would ignite the gases in the cartridge by which the driving piston would be set in motion.'

IV. THE COMING OF THE FOUR-STROKE CYCLE

The value of the compression idea, now generally popular with all investigators, received added impetus at the hands of another Frenchman. In 1862 Alphonse Beau de Rochas published a pamphlet giving the results of an inquiry into the influence of two factors upon economy in the working of gas engines in which compression is used. The two factors in question were (*a*) the volume of the hot gases employed, and (*b*) the extent of the surfaces exposed. Beau de Rochas laid down the necessity for the following factors to be at their maximum value in order to give economical working: (1) the cylinder volume for the least possible cooling surface; (2) the rapidity of expansion; (3) the amount of expansion; and (4) the pressure at the beginning of the expansion.

Beau de Rochas argued by analogy with the heating of the tubes of a boiler. In these, he pointed out, the smaller the tube diameter, the greater the heat efficiency became. Similarly, therefore, in engine cylinders, the smaller the diameter, the greater would be the heat losses from the explosion. For a given fuel consumption, therefore, there should be employed as large a cylinder as possible in order to reduce the heat lost to the cylinder to a minimum, thus permitting the concentration of all the power on to the piston. Further, since loss of heat is proportional to the time, cooling will be proportionately greater the slower the working speed. De Rochas was therefore led to an arrangement in which (1) the suction was induced for the whole of the out stroke of the piston; (2) the return stroke was accompanied by the compression of the mixture; (3) the ignition was arranged to coincide with the 'dead point' or point of termination of the return stroke, causing expansion during the third

stroke—i.e. the second outward stroke; and (4) the ejection from the cylinder of the gaseous products of the explosion during the fourth stroke—i.e. the second return stroke.

Thus was inaugurated, by the vivid genius of this brilliant French engineer and scientist, the four-stroke cycle of operations which has ever since formed the basis of gas and oil engine practice.

The weak point in De Rochas' scheme, as indeed in most designs at this time, was in the arrangements for ignition. De Rochas suggested doing this through the increase in temperature set up in the mixture during the compression to a quarter of the original volume. In the Lenoir engine, too, the electrical device was unsatisfactory.

Nevertheless, in spite of its defects the De Rochas engine laid the foundations for the work of one of the greatest and most successful figures in the history of gas-engine development—Dr. Otto, of Germany. He was born at Holyhausen, in Nassau, in 1832, and he died in 1891. From the age of twenty-two to the year of his death he was engaged in various problems of gas-engine design. The famous 'Otto Silent' engine, known to-day all the world over, was patented by him in the year 1876, and although it was based on the compression cycle inaugurated by De Rochas, it was in every respect superior in workmanship and detail to all its predecessors, and it embodied an efficient scheme of flame ignition. It accomplished, in fact, for the four-stroke cycle principle what the Lenoir engine did for its predecessors, and its economy of working may be gauged from the fact that the fuel consumption was 20 cubic feet per indicated horse-power. It is curious that, with all this success, Otto should have held, as he did, the erroneous idea enunciated by Lenoir that the economy of his engine was owing to the slow expansion due to the arrangement of gases in the cylinder, and that the compression (the real cause of the economical working) was an inessential accident.

Otto was wrong. The advantages of compression are both real and vital and were well described by the late Professor Jenkin in the following terms:

'If I were to compress a gas to 40 lb., a pressure which is used not infrequently, the theoretical efficiency would be 45 per cent. We actually get something like 24 or 23 per cent. We know that one-half of the heat is taken away by external cooling. Thus we find a very close coincidence between the calculated efficiency of those engines and that which we actually obtain; only we throw away about one-half of the heat in keeping the cylinder cool enough to permit lubrication. If we compress to 80 lb. we have a theoretical efficiency of 53 per cent. If we do not compress at all we have a theoretical efficiency of only 21 per cent., so that we have it in our power to increase the theoretical efficiency very greatly by increasing the pressure of the gas and air before ignition.'

How then does it come about that Dr. Otto himself should not have realized the true reason for the efficiency of his own engine? It will be interesting to summarize briefly the theory presented by Otto in support of the specification for his famous design of 1876. Otto held that in all previous types of gas engines, the power was derived from the explosion of an intimate mixture of gas and air. His view was that the explosion caused the excessive evolution of heat, and that the high pressures that resulted fell away rapidly, the excessive heat being absorbed very quickly by the cold cylinder walls. This he declared to be a waste of efficiency, and he therefore asked himself how this waste could be avoided. Two possible lines of approach occurred to Otto. One was to ensure that the expansion should be very rapid, so that the heat should not have time to be lost to the walls. The supposition here was that all the heat was evolved at once, setting up a high temperature.

His second suggestion was to use slow combustion, thus avoiding the setting up of excessive temperatures and pressures altogether. The heat would be evolved gradually, and the pressure set up could be sustained and utilized usefully throughout the whole of the stroke at a moderate speed. Otto followed up this second sugges-

tion fairly closely. He advanced the view that this gradual evolution of heat would be produced by having a heterogeneous or stratified mixture of gas and air rather than an intimate or homogeneous mixture. It was in the endeavour to produce such a mixture in the cylinder that Otto claimed originality of invention. He declared that in addition to the explosive mixture the cylinder must contain a supply of inert gas whose function would be, not to burn, but to absorb the heat of the explosion, and so to protect the cylinder walls from the cooling effect. As to the nature of this inert gas, which must be present in adequate quantity, Otto declared that it could be either air alone (which was capable of supporting combustion) or the products of previous combustion (this naturally was not able to support combustion) or a mixture of both.

Otto next developed his suggestions for setting up such a heterogeneous mixture. He proposed first to draw into the cylinder a charge of air alone, and then a charge of the explosive mixture. Alternately or additionally, he proposed leaving in the compression space of his cylinder a sufficient quantity of the products of the previous explosion, thus ensuring that the whole of the piston stroke was available for absorbing the explosion charge. According to Otto's view, at the beginning of the charging stroke the mixture of coal-gas and air is admitted into the cylinder through the inlet port and mixes incompletely with the inert gas already present, so that the piston itself, for example, is really in contact with exhaust gases entirely. There is therefore a graduation of gas layers from the igniting port to the piston end, from completely combustible to completely incombustible charge. Otto speaks of this as 'the arrangement of the gases', and he assumes this arrangement of layers to persist throughout the period of compression and up to the moment of explosion, by which time he has produced what he calls a 'packed charge'. The layer of inert gases against the piston therefore acts as a protecting cushion to the piston and not only relieves it of the shock of the explosion, but also absorbs the heat and so protects the

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cylinder walls. The flame therefore travels steadily from port to cylinder, the mixture being so arranged that the flame begins at the port at the beginning of the stroke, and arrives at the piston end at the conclusion of the stroke, the charges behind the flame being successively burned out as the flame proceeds on its way forward.

It is important to notice that the complete action involves a cycle of four-piston strokes, and this succession is spoken of as the Otto Cycle. In the first stroke the gases are drawn into the cylinder in their proper proportions and arrangement; in the second or return stroke the charge is compressed; during the third the charge is fired and the piston is propelled forward, and at the return stroke the products of combustion are expelled, leaving a portion in the clearance or compression space at the end of the cylinder. A careful investigation into the relative efficiencies of the Otto and Lenoir engines was carried out in 1884 by Slaby, who showed that whilst the Otto engine gives evidence of heat being added or combustion proceeding in the cylinder during the whole of the expansion stroke of the piston, the Lenoir engine shows a loss instead of a gain of heat during this stroke. In the Lenoir engine all the heat is evolved at the moment of explosion; in the Otto engine 56 per cent. of the heat is evolved at the moment of explosion, and 45 per cent. during expansion. This and subsequent investigations appear to show not only the reality of a heterogeneous arrangement of gases in the cylinder, but also the advantages of such an arrangement.

Where then lies the fallacy in the Otto theory? Subsequent investigations have made it clear that the mistake made by Otto, Slaby and others lay in the mistaken belief that in the Lenoir and other engines preceding the Otto design the explosion was complete and the heat was all evolved instantaneously. Dugald Clerk and others have completely proved that on the contrary such engines evolve little more than half the total heat on explosion, the remainder being evolved during the course of the piston stroke. One test on the Lenoir

engine by Clerk showed an evolution of heat on explosion of 60 per cent., the temperature being about 1200° C. as against about 1600° C. in the Otto engine. Indeed it is difficult to understand how Slaby fell into the error he did. Actually in the Lenoir engine there is much greater cooling of the cylinder walls due to a greater abstraction of heat, but this is due to the much greater amount of cooling surface exposed by the Lenoir engine, and to the longer time of exposure, there being both an absence of compression and a slow piston speed. Hence although as much heat is evolved during the stroke, this is masked by the much greater cooling, and it was this masking that deceived Slaby and those investigators who agreed with them. Actually, too, closer investigation has thrown considerable doubt on the reality of the existence of stratification in the cylinder in the sense in which Otto conceived it. The existence of a cushion of inert gases against the piston has been almost definitely disproved, whilst Dugald Clerk has shown that the mixture in the Otto cylinder is present in explosive proportions close up to the piston. Stratification in the cylinder is not impossible of achievement, but it does not exist in the Otto engine. Nevertheless, as we have already pointed out, the advent of the Otto engine constituted as great a landmark in the history of the internal combustion engine as did that of Watt in the history of the steam engine. It formed the basis of all subsequent development. It created a revolution in road transport through the application of the petrol engine to locomotion, and it was responsible for the remarkable prosperity, through the installation of small-power plant, of the thousands of factories for whose economical working an engine of small horse-power suffices.

CHAPTER IX

IRON PRODUCTION—FROM MEDIEVAL TIMES TO THE ADVENT OF THE STEAM ENGINE

I. INTRODUCTION

IRON and steel are the chief materials of engineering. To trace the development of iron production, and to consider some of the great engineers who made this development possible, must therefore be our next task.

We have already pointed out that long ago the fuel employed in the production of iron was almost entirely of wood. Hence we find early evidences of iron smelting confined to the neighbourhood of woods and forests. The amount of wood required was so great in comparison with the amount of iron produced, that it was always better to transport the ore to the fuel than the fuel to the ore, and when the wood became used up in one area at once to abandon the old furnace, and erect another alongside the next patch of trees. Nevertheless, England produced only an inferior iron during the Middle Ages. Such countries as Spain and Germany easily outstripped her in both quantity and quality of output, and in order to ensure the country a proper supply, not only was the export of iron forbidden, but also the import was encouraged, and was exempted from the protective customs general in other commodities.

This decline in the production of iron in England between the Norman era and the beginning of the Tudor period naturally causes us to focus our attention elsewhere. We have, in fact, to look to Germany as the important

centre of research and improvement, since during this period the labours of the German metallurgists were responsible for the real introduction of *cast iron.* So far, iron had been produced in the simplest of blast furnaces (if not in open hearths), the reduction of the ore being achieved in a single operation. According to the actual method of reduction, the result was either a wrought iron or a steel. On the other hand, cast iron was unknown, apart from any accidental production that might occasionally have occurred. The type of blast furnace in use in Germany was what was known as a Stückofen, and was built up of brickwork. It consisted of two truncated cones placed base to base. The front portion of the hearth was very thin, and could be be taken down to permit of the removal of the bloom of wrought iron after smelting. At first, the height of the Stückofen was 15 feet, and the diameter 5 feet, but now in their desire to reduce the rate of fuel consumption and therefore the cost of production, the German metallurgists began to increase the size of their furnaces and at the same time allowed the ore to remain longer in contact with the fuel. An immediate result was that where previously iron was only produced in a solid or semi-solid state it was now carbonized and could be turned out in a properly molten condition. In other words, where before the iron could only be shaped by intricate forging, *it could now be cast into any desired shape or size.* Further, it was quickly realized that, as by one application of firing the crude metal was extracted from the ore, so by a further application the crude metal would itself be converted into malleable iron. Wrought iron was thus itself a production of cast iron.

It was the advent of cast iron into the world of commercial metallurgy that made possible once more a revival of the iron industry in England. Indeed, towards the end of the sixteenth century the iron manufacture of Sussex was in such a prosperous condition that, where formerly it was necessary to import iron products, there was now quite a considerable export

trade, chiefly in iron ordnance—so much so, indeed, that our Spanish enemies were arming their ships with cannon of English manufacture. The stumbling-block which was to prove fatal to the iron industries of the south, however, was the enormous timber consumption. Originally the clearing of the woods for fuel was welcomed in the interests of both agriculture and industry. But soon the rapid disappearance of the forests began to create alarm. The needs of a growing shipbuilding industry were threatened, and people were worrying, too, about their own supply of domestic fuel. As a result the ironmasters of Sussex found themselves unable to go on, and they were compelled to remove their works elsewhere, chiefly to Aberdare and Merthyr Tydvil in Glamorganshire, where natural deposits of ore were found adjacent to abundant woods. The Civil Wars provided the final blow, and all Royalist ironworks suffered total destruction. By 1674 this destruction was almost complete, and for practical purposes it may be said that the ironworks of the South of England had ceased to be.

To quote Smiles: 'The din of the iron hammer was hushed, the glare of the furnace faded, the last blast of the bellows was blown, and the district returned to its original rural solitude.' All that now remain of the furnaces of the South are the extensive beds of cinders from which material is occasionally taken to mend the Sussex roads, and the numerous furnace ponds, hammer posts, forges and cinder places which mark the seats of the ancient industry.

II. THE INTRODUCTION OF COKE FUEL BY DUD DUDLEY

The threatened decay of the iron industry in England was clearly an alarming state of affairs. It was inconsistent with the well-being of the country, which was again being flooded with iron imports from abroad. It was obvious that the problem could be solved only by

the provision of a suitable substitute for wood charcoal, and the revolutionary suggestion that coal should be used for this purpose was now put forward by one Simon Sturtevant, a German resident in this country. Raw coal contains sulphur, an ingredient which must be kept out of iron as much as possible. Unfortunately in the small furnaces of those times the use of coal was accompanied by a definite tendency for the iron to absorb the sulphur. The solution lay in converting the coal into coke (or ' char ' as it was then called), which is naturally more free from sulphur. Further, by using the coke in larger furnaces, it was possible to reach a higher temperature, and so to obtain a purer iron. In this connexion must be mentioned the name of Dud Dudley (1599–1684), a natural son of the Earl of Dudley. Working in his father's furnaces in and around Dudley, Dud in 1619 succeeded, after many attempts, in producing coke, and in using it to smelt his iron. Dud Dudley was a man of misfortunes. Like so many other pioneers, he encountered almost continual and unmeasured hostility in his revolutionary proposals for the utilization of coal as fuel. The iron-smelters around him belittled his efforts, incited mobs to destroy his works, involved him in lawsuits, and even secured his imprisonment for debt. Yet he persevered and persisted; but all the time he fought his battle single-handed, and practically a hundred years were to elapse before his simple contention, that pig iron should be produced with coke fuel, was to be revived. Dudley first tested his proposals in 1620, but it was not until 1713 that his ideas were again taken up by Abraham Darby, a Quaker iron-smelter of Coalbrookdale, in Shropshire.

III. ABRAHAM DARBY

Abraham Darby was born in 1676 at Sedgeley, near Dudley. He came of yeoman stock, but both his father and his grandfather had added to their normal agricultural work the making of locks and nails. Abraham

served an apprenticeship of some years to Jonathan Freeth of Birmingham, a maker of malt-mills, and later, at the age of twenty-three, he settled at Bristol in partnership with others at the Baptist Mills. Here he soon showed a desire for the improvement of his productions, and experiments were initiated for the substitution of cast iron for the brassware his firm had thus far been producing. The best castings were at this time being made in Holland, and accordingly in 1704 Darby visited that country, studied Dutch methods, and returned with a number of skilled native workers. Shortly after, he withdrew from his partnership at the Baptist Mills, and joined with James Peters and Griffin Prankard in the erection of ironworks in Cheese Lane. Later, in 1708, he took over the lease of some furnaces at Coalbrookdale, in Shropshire.

Various factors combined to make this area of Shropshire ideal for iron production. Its geological formation was such that both coal and ironstone were readily available. The coal seams indeed came to the surface, while near at hand was the limestone of Wenlock Edge. Moreover the whole area was well wooded, forming part of the original Wrekin Forest, so that timber was available both for structural purposes and for the making of charcoal. Finally, the village of Coalbrookdale itself was situated alongside a rapid stream flowing into the Severn, thus offering facilities for both water power and transport. Here, then, was an ideal situation for Darby's new venture. His partners soon withdrew from the business, but he carried on quite successfully alone. After a time, however, the large consumption of timber for fuel began to cause him some anxiety, and he turned to the problem of the utilization of coal.

The credit for the long-sought-for process of the coking of coal has usually been given to Abraham Darby's son. Recent researches have, however, shown that it is to the father that the credit is due, and not to the son. The latter was born on 12th March, 1711, whilst it has been established conclusively that coal was coked and

used in the blast furnace at Coalbrookdale in September, 1718. The Journal of Abraham Darby shows, in fact, records of coal purchases for many years prior to this date. It may be argued that it does not follow necessarily that this coal was used for smelting. The fact remains, however, that the Journal in question gives a very full record of Darby's transactions, but makes no mention of the disposing of this coal elsewhere. Nor, again, was the coal required for smelting work, since Darby manufactured no wrought iron goods. The following entry in Darby's Journal is an example of the indication that he had discovered a method of coking coal, and also that he used some coal for the preliminary roasting of ironstone before introducing it into the furnace :

1709.		£ *s.* *d.*
Apr. 20th.	By Cash paid for Charcking Coles .	00 01 03
Aug. 24th.	By Cash paid Edward Dorall for Coling (? Coking) Coles	01 12 4
July 2nd.	Lawrence Woling By Cash paid him in part for Coles and Iron Wheald ye first blast . . .	30 00 00

Finally, as Ashton [1] points out, there are very few entries indicating a purchase of charcoal fuel, whilst on the other hand the output from the works, not only of pig iron, but also of pots, kettles, fireblacks, mortars, pipes, and other cast ware, was large at this time.

Definite as are these records, however, we are unable to say what exactly was the nature of Darby's process of coking. We have seen that his was not the first attempt. Nor was it probably the first successful attempt. The problem was difficult. Coal is less inflammable than charcoal, and also contains impurities from which the latter is free. Not only, therefore, must these impurities be removed, but also the furnace used must be of such a size that the ironstone is able to remain in contact with the fuel for a much longer time.

[1] Ashton : *Iron and Steel in the Industrial Revolution* (Longman, 1925).

Further, a more powerful draught is necessary to produce a higher temperature than is obtained in the case of charcoal. The difficulty with charcoal was that it tended to be crushed by the great weight of the ironstone, thus limiting the height of the charcoal blast furnace. As a consequence the metal was not rendered sufficiently fluid to enable it to run freely into fine moulds with small channels. The coke furnace remedied this, and so made possible the manufacture of lighter and more complicated castings.

The case in favour of Darby's success is complete, and we must accordingly discountenance the generally accepted view that it was his son who first discovered the process. One can, however, understand why this idea should have got about. Darby was not the type of man to proclaim his invention freely. He was a Quaker, modest and unassuming. He shrank from publicity. Again, his success was probably not continuous, and to some extent it was bound to depend upon the quality of his coal. If it contained sulphur in any quantity, failure was almost inevitable. Consequently the news and details of his process never got far, and it was some considerable time before the coking of coal became general in the industry. There was yet another reason for the slow spread of the process, namely, that its application was at this time only possible within a very narrow range. We must not lose sight of the fact that the manufacture of cast iron ware was really the lesser of two main branches of the industry, the other being the larger production of malleable iron. Cast iron, being hard and brittle, was necessarily limited in its uses, and even for iron which was to be re-smelted to produce wrought iron, the coking process was found to be unsuitable. Then again, even with pig iron itself, the use of coke fuel depended upon the purposes to which the pigs were to be applied. Although, as we have seen, coke-pig iron ran out more fluid and made possible the production of lighter castings, the production by this method was inferior in tensile

strength and ductility to charcoal-pig iron. Consequently the tools and wares demanding greater strength, such as locks, bolts and ploughshares, still had to be made with charcoal fuel.

There is every reason, therefore, why the lone part played by Abraham Darby the elder should have remained obscure. This pioneer of engineering, however, deserves his place in history for a twofold contribution to his profession, namely, his improvements in sand moulds and boxes, and his introduction of the coking process. Both made a sturdy basis for the development of one of the great industries that have given to our country the name of the 'Workshop of the World'.

IV. THE INVENTION OF PUDDLING

We now pass to another important stage in the development of the iron industry—that of the invention of the puddling process. Wrought iron was now being produced by a twofold process—a first smelting to produce cast iron, and then a conversion of the cast iron by a second smelting into a decarbonized malleable iron. Up to the time of the Darbys of Coalbrookdale this second process had been carried out in a small hearth called a 'Finery', resembling a smith's forge, the fuel being wood charcoal. Charcoal fuel was, however, very extravagant for this purpose; for whereas 16 cwt. of charcoal would suffice to produce a ton of pig iron, a ton and a half of pigs, and therefore 24 cwt. of charcoal, were necessary to produce a ton of bar iron. Naturally, therefore, there was great anxiety to find some means of utilizing coal for this operation. So we come to the invention in 1766, by the Brothers Cranage, of the *reverberatory furnace*, so called because the flame of the current of heated gases from the fuel is caused to be reverberated or reflected downwards upon the substance under operation before passing into the chimney. The Brothers Cranage rendered the iron malleable by separating the hearth that held the pig

iron from the grate containing the pit-coal fire by a low bridge of bricks. The flame passed over this bridge and was deflected downwards so as to play on the metal, thus avoiding direct contact between iron and fuel. The following is a contemporary description of such a furnace:

> 'It consists essentially of three parts—a fireplace at one end, a stack or chimney at the other, and a bed between both on which the matter is heated. The fireplace is separated from the bed by a low partition wall called the fire-bridge, and both are covered by an arched roof which rises from the end wall of the fireplace and gradually dips towards the farthest end of the bed connected with the stack. On one or both sides of the bed, or at the end near the stack, there are openings through which the ore spread over the surface of the bed may be stirred about and exposed to the action of the air. The matter is heated in such a furnace by flame, and is kept from contact with the solid fuel. The flame in its course from the fireplace to the stack is reflected downwards or reverberated on the matter beneath.'

By this means it was definitely possible to use coal fuel instead of charcoal for the decarbonizing of pig iron, and the resulting malleable iron could be removed to the forge hammer in a red-hot condition and worked into bars or into any other shape required.

The next step was due to Peter Onions, of Merthyr Tydvil, who in 1783 adopted and patented a new process. He charged his furnace with pig iron, and then closed and sealed its doors with sand. The combustion of the fuel was then maintained by a blast from below. Such a furnace was known as a 'Puddling Furnace'. The blast was maintained until the liquid metal frothed and thickened (due, as a matter of fact, to the rise in the melting-point consequent upon the iron becoming more pure on giving up its carbon), when a workman would open the door, insert an iron bar, and twist up round its end a mass of metal. This would be withdrawn and removed to the forge to be worked, the door of the furnace being meanwhile reclosed.

The real credit for an efficient puddling process is, however, undoubtedly due to Henry Cort (1740–1800),

who, as a result of researches in connexion with the supply of iron to the British Navy, patented in 1784 a puddling process which, though it utilized both the idea of the reverberatory furnace of the Cranages and of the puddling furnace of Onions, was far superior to both. Cort employed a reverberatory furnace the bottom of which was of sand and was shaped hollow to contain fluid metal, introduced into it in ladles from the first process of pig iron production. The fuel used was pit-coal, and after charging, the furnace was closed until the metal was sufficiently fused. The workman would then open an aperture and introduce a rod of iron, with which he would stir the metal. An 'ebullition' would at once take place, the carbon being extracted from the cast iron to the accompaniment of a bluish flame. The metal now separated out from the slag, and the iron thus produced was withdrawn in lumps or loops for working as desired.

Another important process used by Cort was that of piling up a number of bars with tapered ends in brick fashion, i.e. one across and over another, to amount in the aggregate to anything up to half a ton. The whole could then be introduced into a furnace and heated to a welding heat, at which point it was brought under a large-sized forge-hammer and welded into a single mass of a size greater than had been possible before. Finally, we should also mention Cort's use of milling rollers through which he passed his iron with the twofold purpose of freeing it from cindery impurities and of compressing it to a 'tough and fibrous state', though many claimed that as much cinder was compressed into the metal as was squeezed out of it. The use of rollers was, however, by no means novel in Cort's days. As far back as 1615 hand rollers had been employed in the production of lead sheets, and tin-plate manufacture was being carried on in the eighteenth century with the aid of rollers driven by water power.

The influence of Henry Cort in the technology of iron, and therefore upon the engineering of his day, was real

and great. There was, however, much waste in his puddling process, owing chiefly to the fact that the decarbonization was effected by fluid oxide of iron produced from the pig iron itself by atmospheric oxidation. This was partially met, chiefly in the case of a much used grey iron rich in silicates, by a preliminary refining process introduced in 1790 by Homfray, of Tredegar, but even so Cort's process persisted down to recent times.

This then was the state of affairs in iron production on the eve of the next great advance in technological method—an advance which was to create a virtual revolution in production far greater in extent than anything hitherto achieved. We refer to the invention of the hot blast, with which the really modern period in iron production may be considered to have been inaugurated.

V. THE INVENTION OF THE HOT BLAST

When a current of cold air is employed in a furnace, it will be obvious that since nitrogen takes up four-fifths of the toal air, much of the heat is absorbed in heating a gas which plays no part whatever in the process of combustion. There is therefore an unnecessary cooling effect. This can be avoided by the simple procedure of heating the air before it enters the furnace, and so we get the suggestion of the hot blast, due in the first place to J. B. Nielson in 1826. The suggestion came at a time when the current theory in vogue was the exact opposite. The accepted notion was that the colder the air current, the more efficient was the furnace, and indeed this notion was so far put into practice as to prompt the ironmasters to pass the air over cold water, to paint the regulator white, and even to pass the air pipes through ice. Nevertheless, in 1829 Neilson's patent was tried at the Clyde Iron Works, the air being heated to 300° F. before entering the furnace. The effect was unmistakable, the consumption of coal fuel per ton of iron at once dropped from about 8 tons to about 5 tons ;

and when by 1833 the temperature of the blast was raised to 600° F., the fuel consumption dropped yet farther to 2¼ tons per ton of iron produced.

Curiously enough, it is unlikely that Neilson had any real scientific grounds for asserting his claim. It was probably a lucky guess on his part—or perhaps what in America is called a 'hunch'. Nowadays, of course, we know a number of reasons why the hot blast is the more economical. In addition to the one stated above, for example, there is the fact that in the lower part of the furnace the oxidation of the carbon is only partial, forming carbon monoxide (CO) with cold blast, as against complete oxidation to form carbon dioxide (CO_2) with the hot blast. The heat generated per unit of carbon in this latter case is in fact about three times that of the former case. Now actually we find that between 1200° C. and 1300° C., carbon dioxide dissociates itself or splits up into carbon monoxide and oxygen. This means that carbon monoxide can only be completely burned to carbon dioxide when the temperature of combustion does not much exceed 1300° C. Hence the hot blast, by leading to the immediate formation of CO, yields a higher temperature in the hearth than would be obtained if CO_2 were produced there.

In the original arrangement as employed by Neilson in 1829 at the Clyde Iron Works, Glasgow, a small iron rectangular heating chamber 4 feet × 3 feet × 2 feet was set in brickwork with a grate below it like a steam boiler. The cold blast entered over the grate and passed out at a temperature of about 200° F. Each of the three twyers feeding the furnace with air was provided with one of these heating boxes. The result was encouraging, but the apparatus was quickly seen to be inefficient. The wrought iron chamber exposed little heating surface to the blast, and soon required renewal. It was accordingly replaced by a cylindrical cast iron tube set horizontally in the heating chamber. This was an improvement, giving a higher temperature to the air, but it led to much trouble owing to the expansion

and contraction of the pipes. So we come to the tubular cast iron oven (Fig. 30), first erected in 1832 at the Clyde Iron Works. The blast furnace was supplied with three twyers, each having a store of brickwork heated by a fire grate underneath, through which the air was led by a series of semicircular cast iron pipes arched over the fireplace. This system found immediate favour, and before long was in general use in an improved

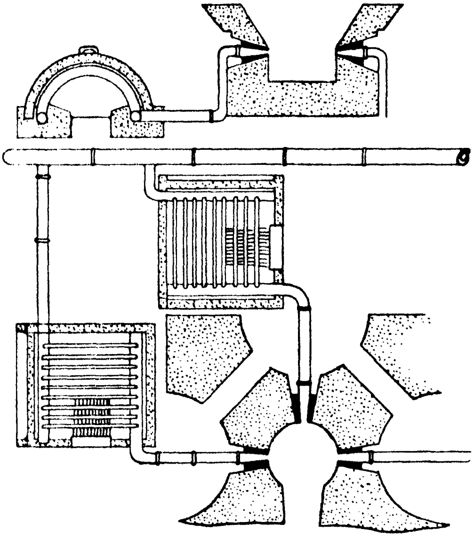

FIG. 30.—Iron Production—Neilson's Invention of the Hot Blast: 1829 and 1832.

form in many ironworks. Expansion troubles were reduced by employing a **U**-shaped pipe, and the heating surface was increased by using an elliptical cross-section for the castings. The fuel used in these hot-blast furnaces had been solid fuel applied directly, but in 1833 Faber du Four suggested utilizing the waste gases from the blast furnace itself, the combustion of which

was a source of heat that had hitherto been allowed to waste.

Following, however, the regenerative furnace invented by Siemens, to be described in the next chapter, a great advance in hot-blast stove design was effected by E. A. Cowper in 1860. The Cowper stove is shown in section in Fig. 31. The outer cylindrical chamber of wrought iron (known as the regenerator) is about 60 feet high by 28 feet in diameter and has a dome-shaped top. It is lined inside with firebricks, and has a circular flue

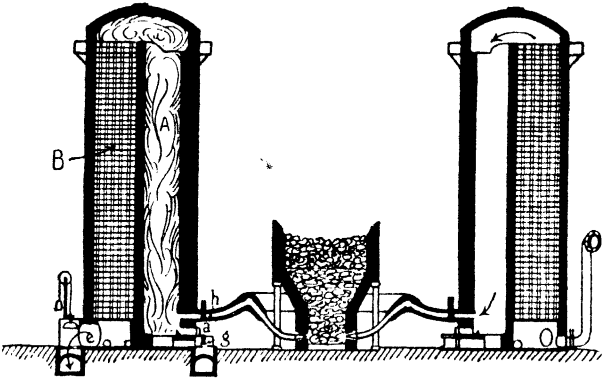

FIG. 31.—The Cowper Hot-blast Stove, 1860.

A reaching from bottom to top. The remaining space of the chamber B is heaped up with loose firebrick. Originally there was no binding material of any kind, but in a later improvement (about 1875) the bricks were arranged in rows, with alternate bricks projecting so as to form vertical channels. (In modern practice a hexagonal 'honeycomb' brick is employed, giving in effect a series of vertical hexagonal channels.) The waste gases from the blast furnace enter the Cowper stove through a gas-valve *g* as shown in the figure, whilst the air which must be used with it to make combustion possible enters through an air-valve *a*. Both intermingle

in the flue at the base of which combustion takes place. The heated products of combustion are carried upwards, over, and downwards through the honeycombed bricks (which become red-hot) and out to the chimney through an exit valve *e*. This continues till the brickwork is thoroughly red-hot. The inlet valves are then closed, and a cold blast is admitted in an opposite direction through the brickwork, to be delivered at a very high temperature to the furnace through the hot-blast valve *h*.

In order that the process may be continuous, at least two hot blast stoves must be provided for each furnace, so that whilst one is delivering the hot blast, the other is having its brickwork heated. In some cases there are as many as four per furnace.

One of the most striking examples of the influence of the hot blast on the iron industry was seen in the case of Scotland. In the West there occur large deposits of an iron ore known as black band ironstone, which was first identified and studied by David Mushet in 1801. This had proved practically unworkable with the cold blast, so that the Carron Iron Works, for example, which were established in 1760, used to import their ore from England, and mix it with Scotch ore and limestone. Mushet, however, showed that black band ironstone was at once amenable to reduction with the aid of the hot blast, and in 1825 this ore was able to be used alone. The influence on the Scotch industry was immediate. In 1830 the production of pig iron was 37,500 tons; in 1840 it had risen to 200,000 tons. Yet one other result requires mention. In South Wales it was found that anthracite coal, the occurrence of which was plentiful locally, could be successfully employed in the blast furnace with the hot blast where it had proved useless with the cold blast, and so both the coal and the iron industries of South Wales received added impetus. In America, too, where anthracite coal occurs abundantly, the effect was instantaneous, and so began the huge industry of iron production with which the name of Pensylvania is associated.

CHAPTER X

THE ERA OF CHEAP STEEL

I. THE BESSEMER PROCESS

WE turn finally to what, from the point of view of its general industrial value, was the most important advance in the history of the iron industry, namely, the discovery by Henry Bessemer of a method of producing cheap steel.

We have seen that although wrought iron and steel were known and were being produced, the method was both slow and costly. To-day so much constructional work depends upon steel that it is a little difficult to realize that before Bessemer's great discovery in 1855 steel could enter very little into the scheme of human life, owing to its prohibitive cost. Our railroads, our steamships, the frameworks of our great buildings, and hosts of different types of machines, all depend for their strength and efficiency upon this product. It need scarcely be pointed out, therefore, that to Sir Henry Bessemer the world is indebted for one of the most beneficial inventions in the history of engineering.

Henry Bessemer was born at Charlton, in England, in the year 1813. At the age of eighteen he designed a method for engraving on steel. This was, in fact, merely the beginning of a long record of inventions. He early realized, however, that he could not devote his time to experiment without adequate means, and it is fortunate for humanity that in the course of time he was enabled to turn his gifts to practical account as the

result of an invention of a highly lucrative nature. He had become interested in gold printing, for which bronze powder was used. This process was costly, and he could not understand why it should be so. The material then used was imported from Germany, and it occurred to Bessemer that he might be able to produce a suitable material much more cheaply. In this he succeeded to such an extent that he was able to sell the commodity at about one-thirtieth of the price at which it was imported. He was thus able to amass sufficient to enable him to proceed with his inventions.

Steel is an almost pure compound of iron and carbon, and from the point of view of this carbon content, it is intermediate in composition between wrought iron and cast iron. It also possesses in a great measure the most valuable properties of both. Good steel contains from 0·7 to 1·7 per cent. of carbon and a small quantity of silicon. It is distinguished usually from cast iron by its fine close grain, and its tenacity exceeds that of wrought iron. Thus while a one-inch bar of good wrought iron may break with a load of 30 tons, a bar of good steel of the same size will withstand 75 tons, or even more. Further, according to the treatment it receives, its properties of hardness, elasticity, etc., can be varied. Thus, if it is suddenly 'quenched' in water when red-hot, it becomes exceedingly hard and brittle and elastic. The hardness and brittleness can, however, be reduced by a suitable amount of tempering. Virtually the problem of producing steel from cast iron is that of partial decarbonization. Hitherto, as we have seen, this had been achieved by an additional furnace operation.

The idea of the production of a cheap steel had suggested itself to Bessemer as a result of the generally known desire of the French Emperor, Napoleon III, to find a material with which he could improve his artillery. The production of steel by the methods we have already described was at this time costing anything up to £70 per ton. Naturally very little was produced as a consequence. The idea occurred to Bessemer that he might

improve the cast iron then in use by adding to it a small quantity of steel. He submitted a sample of this to Napoleon III, and proved his work to be so promising that the French Government commissioned him to deliver a 10-ton gun. It was shortly after this that Bessemer conceived his epoch-making idea of producing an improved wrought iron from a mass of molten pig iron without the intervention of the puddler, by the simple device of driving a current of air through the molten mass so as to burn out the impurities from the pig iron. He tested this on a small scale initially with a blow torch and a laboratory crucible, and the result was an astonishing success. At first Bessemer employed a mixture of hot air and steam for his draught, but the steam was found to have an injurious effect. When after this he used air alone, he was satisfied that he had produced a much higher temperature than ever before, sufficient in fact to render malleable iron as liquid as water. Within half an hour Bessemer had converted cast iron into a pure and far tougher wrought iron that was found to answer every test. He then proceeded to large-scale experiments, carried out in his factory at St. Pancras.

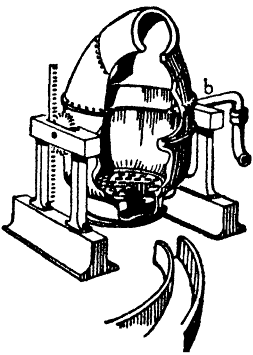

FIG. 32.—Steel Production—The Bessemer Furnace.

At first the results were none too satisfactory, but after a time he used a large egg-shaped crucible or converter about 3½ feet in diameter (Fig. 32), and he mounted this on trunnions in order to rotate it into any desired position. One of the trunnions was hollow to admit the air blast through a pipe to the base of the vessel. This pipe naturally swung round with the converter, whose base was perforated by about fifty holes, each of ½ inch

diameter. The iron required for the operation was melted in a furnace placed with its upper half above the level of the converter, so that when the latter was suitably rotated it was in a position to receive the molten iron by way of a sand-lined trough leading from the furnace. The blast was first turned on at a pressure of 15 lb. to the aquare inch. Hydraulic power was then applied and the converter was brought slowly to an upright position. When all the silicon and carbon was consumed the converter was slowly rotated back into the horizontal position and the blast was shut off. A certain weight of cast iron of known composition was then run in, the blowing was resumed, and the vessel brought back to the upright position. The blast was continued until the newly introduced ingredients had been absorbed. The vessel was then once again lowered, the blast shut off, and the contents of the converter were run out through a vessel of wrought iron into the moulds in a stream about 1 inch in diameter.

It will be seen that by this means the steel, after being entirely deprived of its carbon and silicon, is re-supplied with the requisite percentage of carbon by the addition of the cast iron of known composition. It was for this reason that the arrangement was called a 'converter'. It was made of wrought iron in two parts, an upper half and a lower half. It was lined inside with a thick infusible coating, made from ground firebricks and a certain kind of sandstone. The two portions were rigidly bolted together. A pipe led to the perforated base, and was connected to a powerful engine and blower. The converter itself was encased in what was known as a blast box, and near the top of the converter was a hole which acted as a vent for the flame produced during the blowing operations. Let us consider the process a little more closely. The blast was first started and a half ton or so of molten pig iron was then poured in. There at once followed a process of oxidation of the carbon and silicon contained in the molten iron. The air rushing through the liquid kept it in a state of

constant agitation, the combination of the oxide with the carbon not only keeping the temperature from falling but even causing it greatly to increase. After some twenty minutes, all the carbon diffused through the iron having been burnt up, the metal itself began to combine with the oxygen, producing iron oxide. This, being itself well mixed with the remainder by the violence of the draught, was brought into contact with any silicon or earthy matters present, rendered them fusible, and caused them to appear as a frothy slag. After about half an hour the process was virtually complete and the liquid iron, freed from carbon, was run out at a tap-hole. Clearly in this process, if only the draught could be stopped at the correct point, any portion of carbon desired could be left in combination with the iron, thus producing a good cast steel. In practice, however, the determination of the precise point of decarbonization at which the operation should be stopped was very difficult to determine, and this scheme had to be abandoned in consequence.

The date of Bessemer's invention was 1855. Commercially it was at first not very successful, and a number of ironmasters who had taken up the invention met with failure in the enterprise. Bessemer received a considerable amount of abuse in consequence. The reason for this failure was that the composition of the pig iron used varied in the different firms, and Bessemer quickly realized that the nature of the pig iron must be a subject of further investigation. He was himself somewhat ignorant of chemistry, and he therefore enlisted the services of an expert chemist. It became evident that he had himself, by a wonderful stroke of good fortune, utilized just the right kind of pig iron necessary. With the aid of the chemist he discovered that whilst the good steel he had himself produced was low in phosphorus and in sulphur content, the bad examples produced by others were high in both of these ingredients. Bessemer had parted with the entire rights of his process for ten thousand pounds each to five

different firms, but he persuaded these five disappointed manufacturers to sell their rights back to him. It was fortunate that he did so, as otherwise he would never have acquired the huge fortune which his invention was later to bring him.

Bessemer now continued his experiments. He learnt that the ore he had originally employed came from West Cumberland, and was low in its phosphorus content. He therefore obtained a further supply and applied his process to it at his works in Sheffield, whither he had by now removed. He found the result to be very disappointing. Analysis showed that although the original ore was relatively free from phosphorus, the resulting steel was rich in this undesirable ingredient. 'How', he asked himself, 'had this come about?' He went to West Cumberland and visited the ironworks from which his raw supplies had come. Passing through these works he noticed a heap of rock, and on inquiring he found that this was the flux used by the ironworks to obtain their product. He questioned the manager as to its nature, and was told that it was nothing more nor less than puddled furnace-cinder. In a flash Bessemer realized the truth. This puddled furnace-cinder must necessarily contain a high percentage of phosphorus, and clearly could not have been used in the original samples of ore supplied to him. He arranged with the firm that for the future such pig iron as he required would be prepared for him from straight ore without the use of the puddled cinder, and such pig iron, i.e. iron having a low phosphorus content, has ever since been known as Bessemer iron. The results were completely satisfactory, and from that time onwards the firm of Henry Bessemer & Company flourished.

Almost immediately Bessemer was able to market his product more cheaply by £20 to £30 per ton than the steel produced by the older methods. His steel did not at first receive general recognition, but after a time an increasing number of ironworkers paid him a royalty for permission to use his process.

The ultimate results were far-reaching in the extreme. Thus a complete revolution was effected in the manufacture of rails for the rapidly growing railroads. These had been made of wrought iron. Now the much stronger steel was employed. By 1866 Bessemer enjoyed an income of some half million pounds per annum. He retired in 1870, and was knighted eight years later. He died in the year 1898, and perhaps the most striking tribute to his work is the fact that in the year in which he died, no less than 4,666,000 tons of steel were produced as compared with 50,000 tons in the year 1855, when he had lodged his first patent.

II. SIEMENS' STEEL

It was but natural that the success of Bessemer should draw the attention of a large number of investigators to the whole problem of steel production. Some of these met with a partial success, but one of them, Sir W. Siemens, originated a new process for the manufacture of steel that not only rivalled the Bessemer process but ultimately largely supplanted it.

Siemens was born at Lenthe, in Hanover, in the year 1823. He came from a family of famous scientists and inventors. He was educated at the Polytechnic School of Magdeburg, and later proceeded to the University of Gottingen. He began his career of invention at the age of twenty, when he paid his first visit to England in order to introduce a method by which silver could be deposited electrically with a smooth surface instead of the crystalline surface which had heretofore been obtained. Presumably this visit must have made a strong appeal to Siemens, for a year later, in 1844, he returned to make England his permanent home.

Both he and his brother Frederick were greatly interested in the new theories of heat and energy which were then replacing the old doctrine of caloric, and as a result of which the conception of the reversible cycle in engine practice was now being utilized. In 1857 Frederick Siemens suggested to his brother the appli-

cation of the regenerative principle for producing a high temperature in furnaces. In the succeeding years a number of furnaces embodying this principle were designed. As they increased in size, however, various practical difficulties arose, as a result of which Siemens adopted the system of converting his fuel into gases before burning it. The first furnace of this improved type, patented in 1861, was worked with gas producers and firebrick regenerators each of which were separate from it. It was soon used on a considerable scale, and its advantages and economy of working made it very popular. Generally speaking, furnaces using gaseous fuels are but slight modifications of the reverberatory type of furnace, due originally, it will be recalled, to Henry Cort. In fact, if the fireplace of the reverberatory furnace is made very deep, and is worked with a thick layer of fuel, it becomes a virtual gas-producer. The Siemens Brothers were not the first to design such a gas furnace, but theirs was the first that became commercially successful.

The principle of the regenerative furnace is very simple. Each furnace is provided with four chambers or regenerators, suitably placed and filled with a chequer-work of firebrick. The air and gas are applied at one end and burnt, and the products of combustion are passed on at the other end to the chimney through one pair of regenerators. When these regenerators are hot the air and gas reach the furnace at a high temperature, and the products of combustion are now passed away through the other pair of regenerators. The direction is thus reversed periodically, say every hour, so that the regenerators are kept very hot, and while two are always being heated, the other two are heating the air and gas.

The regenerative furnace had many advantages. Although the temperature inside was very high, the gases escaped at a low temperature, little more than 212° F., and therefore the heat which they carried away was small and the efficiency of the furnace was correspondingly high. Further, the flame could be kept

perfectly steady for any length of time, and it could be made to function as an oxidizing, reducing, or neutral agent as required. Nowadays furnaces of this kind are sometimes no less than 40 feet long and 15 feet wide.

Siemens then directed his attention to the manufacture of steel on the hearth of this furnace. The process consisted in making molten steel out of pig or cast iron and scrap, the waste pieces of steel and iron being melted together on the 'open hearth', as the uncovered basin-like bottom of the reverberatory furnace was called. Fig. 33 shows the general scheme of this process. The hearth of the furnace A, nowadays some 40 feet in

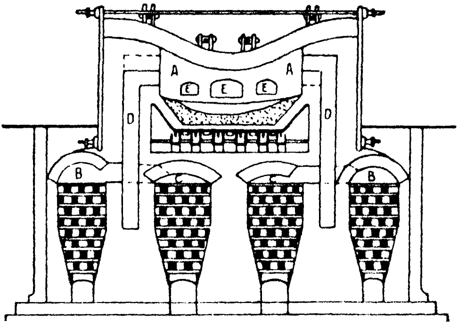

FIG. 33.—Steel Production—The Siemens Process.

length, 12 feet in width, and 2 feet in depth, is lined with limestone, silica sand, or dolomite. The fuel used is either natural gas or sprayed oil. The chequer-work of brick is arranged below the furnace so that the heated products of combustion escaping from the furnace may be conducted through it, thus heating the bricks to a high temperature. The air necessary for combustion and the gaseous fuel (unless decomposed by heating as in the case of natural gas and sprayed oil) are pre-heated by passing them over the hot bricks, so that the temperature reached during combustion is greatly increased. The gas entering through the gas chequers BB comes into

contact with the hot air from the air chequers CC, and a vigorous combustion results, the flame passing above and over the cast iron and lime with which the furnace is charged. The products of combustion escape through suitable flues. At the temperature reached the carbon in the cast iron is removed in the form of oxide, the escaping gas giving the molten metal the appearance of boiling. The silicon, phosphorus and sulphur unite with the oxygen, and the resulting compounds combine with the lime to form a slag. This slag rises to the surface of the melted charge and is easily removed. When a test shows the desired percentage of carbon to be present the molten steel is run into large ladles and then into moulds.

To-day by far the largest amount of steel produced is made by this process, an average furnace producing about 50 tons of steel in a given charge, about eight hours being required. The Siemens process was so far an improvement upon the Bessemer process that it has, as we have already mentioned, largely superseded it. The Bessemer process has the advantage that steel can be produced from pig iron without any expenditure of fuel. On the other hand, the Siemens process, although it requires fuel, gives a larger yield from a given weight of pig iron, the production is more uniform, and the operation is more under control. Generally speaking, while Bessemer's process is still greatly employed for the production of steel rails, Siemens' finds a much wider application. It is especially suitable for steel intended to be cast for bridge and general constructional work, and for the manufacture of ships' plates.

III. THE BASIC PROCESS

We turn finally to a further method of steel manufacture known as the Basic Process. We have already pointed out that the ordinary Bessemer process, conducted in converters lined with silicious material, did not remove the phosphorus present in the original pig iron. Collyer in 1856 showed that this objectionable impurity could be removed by the use of lime, and later

metallurgists confirmed this. It was therefore necessary to employ a base of some kind so that steel could be derived from iron with a phosphorous content. The difficulty, however, was to put this conveniently into practice. One of the earliest suggestions to this end came from Heaton, who employed sodium nitrate in order to use the base with oxygen. The operation was, however, so difficult and costly that the method had to be abandoned. Later, Sir Lowthian Bell experimented with molten cast iron and fluid oxide of iron at comparatively low temperatures. This was referred to as the 'Washing Process', and was in fact adopted by the Krupp Works in Germany for the partial dephosphorization of pig iron as a preliminary to its further use.

The ultimate solution of the problem was an achievement the credit for which is due to two cousins, Sidney Gilchrist Thomas and Percy C. Gilchrist. Thomas was born in 1850, and although intended for the medical profession he entered the Civil Service. Science, however, had a natural appeal for him, and metallurgy in particular occupied the greater part of his leisure hours. His cousin Gilchrist was a year younger and graduated at the Royal School of Mines (now an integral part of the Imperial College of Science) and took up the profession of chemistry. These two began an early collaboration, and in the course of time devoted their attention to the practical solution of the problem of dephosphorization. In this they were successful. Their invention was based upon the substitution of a basic lining for the acid material previously used in the Bessemer and Siemens processes, and during the operation they added a quantity of quicklime to permit of its combination with the silicon and phosphorus. By this means they were able to save the lining as much as possible. The lining in question was composed of well-burnt lime, made from dolomite or magnesian limestone. This was finely ground and mixed with dry tar, to enable it either to be pressed into bricks and afterwards baked, or alternatively to be rammed, so as to form a lining to

the converter. The first announcements of his process were made by Thomas in 1878, but they attracted little attention. Fortunately the invention was taken up by E. W. Richards of Middlesbrough, and his success was so striking that a public demonstration was given in 1879. The attention of metallurgists and engineers from all parts of the world was now drawn to the process, as a result of which it has seen uninterrupted development of a rapidity that exceeded even that experienced by the Bessemer process.

We have now considered the three chief processes employed in the making of steel. The present position is not without interest. Up to 1906 all the basic steel produced in America was being made by the Siemens process. In Germany, on the other hand, the Bessemer process was practically universal. In England, although basic steel is produced in considerable and steadily increasing quantities, the output cannot compare with those of Germany and America. In Germany, there are large deposits of phosphorous ores, the natural occurrence of which carries its own commerical consequences. In recent years, however, both in Germany and America the open-hearth process has become increasingly popular. A new impetus has been offered by the recent invention of a modified open hearth by B. Talbert, an Englishman. Talbert announced his invention in 1900. Conversion into steel is effected in a large gas-fire metal mixer shaped like a horizontal cylinder. Talbert's idea was to treat fluid cast iron in large bulk with comparatively small doses of oxidizing agents. These oxides rapidly melt as they are added, and the resulting reaction generates so much internal heat that the metal maintains its fluid condition with no necessity for adding much external fuel. The vessel contains some 150 tons of fluid metal, and works continuously. As charges of from 10 to 20 tons are drawn at intervals, corresponding charges are added. The Talbert process is so far successful that there is no doubt that it will occupy a place of rapidly increasing importance in the future industry of steel production.

CHAPTER XI

CONCLUSION

LIMITATIONS of space now compel us to a close. Inevitably we have been able to do little more than skim the surface of a very great story. Engineering progresses in its accomplishments and in its endeavours literally day by day. Its activities and its investigations in the past constitute a record that has yet to be told, if ever it can be, in the space of one volume. In a small book such as this the task has been so manifestly impossible that we have not even made a pretence at it. As in the case of an earlier volume in the same series,[1] we lay claim to no more than an attempt to pay tribute to a large army of investigators and pioneers in engineering by drawing attention to the work of a specific few. These have been chosen in no special order of merit but have been selected in accordance with a self-imposed restriction to the story of the progress of Man's control over power and materials. This we have regarded as the fundamental of the whole science and practice of engineering, for upon Man's mastery over these two factors has been erected the whole superstructure of engineering achievement—the design and manipulation of workshop tools and machinery, the supply of road, rail and steam transport, the design and construction of roads, docks, canals, harbours, bridges, and viaducts. All these aspects of our subject have been left untouched. Consequently for every honoured name we have mentioned in this book, there are at least a score of others

[1] Hart: *The Great Physicists* (Methuen & Co.).

equally worthy of mention, and equally deserving of our tribute, that have in fact been omitted. But the spirit and service of science is common to them all. Collectively and individually they have played their part and have made their contribution for the betterment of civilization; and if to the majority of us it is given to do little more than live our lives profiting daily, both physically and mentally, because the great engineers of the past have done what they have, let us at least not forget the debt that we owe to them. We tend, of course, to take things too much for granted. The whole world is covered by a vast network of illustrations and examples of engineering progress. If this small volume of tribute does no more than cause the reader to pause and ponder over the fact that the roads and bridges and machinery that teem with life and activity and power also teem with history, our work will have been adequately done. The lessons of history are the heritage of posterity, and an all-too-frequently forgotten lesson is that of gratitude to those to whom gratitude is due. Among those deserving of the grateful rememberance of mankind we, for our part, claim to include 'The Great Engineers'.

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